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MILITARY STANDARIZATION HANDBOOK, REAL TIME ELECTRO-OPTICAL IMAGING SYSTEMS TUTORIAL GUIDE TO THE SPECIFICATION OF PERFORMANCE

Philco-Ford Corporation

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MILITARY STANDARDIZATION HANDBOOK

REAL TIME ELECTRO-OPTICAL IMAGING SYSTEMS

TUTORIAL GUIDE TO THE SPECIFICATION OF PERFORMANCE

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PROPOSED MIL-HDBK-__________

16 December 1971

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MILITARY STANDARDIZATION HANDBOOK

REAL TIME ELECTRO-OPTICAL IMAGING SYSTEMS

TUTORIAL GUIDE TO THE SPECIFICATION OF PERFORMANCE

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FSC

DEPARTMENT OF DEFENSE
WASHINGTON 25, D.C.

MIL-HDBK-
Real Time Electro-Optical Imaging Systems,
Tutorial Guide to the Specification of Performance
16 December 1971

1. This standardization handbook was developed by Aeronutronic Division of Philco-Ford Corporation, for the U. S. Army Missile Command, Redstone Arsenal, Alabama, on Contract No. DAAH01-71-C-0433.

2. This document provides basic and fundamental information on the use and performance of real time electro-optical imaging systems. It will provide a comprehensive overview of the real time imaging problem for individuals with no assumed prior background in imaging system design or terminology. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

3. Every effort has been made to reflect the latest techniques of analyzing real time imaging systems. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions.

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SYMBOL TABLE

A	area (photosensor, etc.)
A_{sq}	amplitude square wave
C	contrast
C_U	universal contrast
C_T	television contrast
C_R	apparent universal contrast
C_o	inherent universal contrast
D	diameter, clear aperture
D^*	detectivity
D_T	target maximum dimension
E	irradiance, illuminance
F	f/, or f#, or f/number
$\dot{F}$	frame rate
G	photon rate
H	sky/ground ratio or horizon/background ratio
I	radiant intensity
K	efficacy
L	radiance, luminance

M	magnification
M	emittance, exitance
N	resolution, TV lines
N_e	equivalent line number
N_n	resolution element (area) per classification task
P	period of a sine wave
Q	radiant energy
R	responsivity
R	ratio contrast
S	luminous sensitivity
T	temperature in Kelvins
U	photon energy
V	luminous efficiency
V_2	meterological range
a	target image size
a_D	area of individual scanning aperture
b	aspect ratio
c	speed of light
d	sensor diameter
e	electronic charge
f	focal length
f_H	electrical frequency generated by scanning
f_m	maximum frequency of input function
g	image size in scan lines

h Planck's constant

i current

k interlace ratio

k_v Kell factor

k_s system configuration constant

k_B Boltzmann's constant

m modulation

n index of refraction

n_d number of detectors in a FLIR array

n_f number of scan lines per frame time

n_r number of active scan lines per frame

p angular variable for total field of view (azimuth)

q angular variable for total field of view (elevation)

$\tilde{r}$ MTF (sine wave response)

$\overset{\sqcap}{r}$ square wave response

r range

t_d dwell time of a scanning aperture

t_e eye integration time

t_f frame time

t variable, time

u angular variable, for image ray bundle size

v velocity of light in a dielectric

w image size of a line pair

Δ constant, SNR_D equation

Λ	angular variable, sightline jitter
Φ	radiant flux
Ω_T	target solid angle subtent
α	absorbtance
β	total angular display height
β_T	displayed target height
γ	input/output characteristic
δ	diameter of a circular diffraction pattern
ϵ	emissivity
η	quantum efficiency
η_c	cold shield efficiency
η_s	scanning efficiency (FLIR)
η_H	horizontal scanning efficiency (TV)
θ	angular variable for angle of projection
θ_d	instantaneous field of view for FLIR detector, discretion of scan
θ_n	instantaneous field of view for FLIR detector, normal to scan
θ_e	angular subtent requirement for the eye
θ_T	angular subtent of the target
$\theta_{T_{min}}$	minimum dimension subtent of the target
λ	wavelength
μ	prefix for micro (10^{-6})
ν	spatial frequency
ν_T	spatial frequency per target dimension
ν_o	spatial frequency cutoff

ξ	angular variable for dimension in direction of scan (FLIR)
ρ	reflectivity
ρ_n	noise roll-off factor (FLIR)
σ	standard deviation
σ_B	Stefan-Boltzmann constant
σ_a	atmospheric attenuation
τ	transmittance
τ_a	atmospheric transmission
τ_o	optical transmittance
ϕ	angular variable, angle of incidence, reflectance
ϕ_e	angular variable, phase of the moon
ψ	spatial frequency, angular
ψ_o	spatial frequency cutoff - angular
ω	solid angle
Δf	bandwidth
f/	f/number, also same as F
S/N	signal to noise ratio
ℓ	bar length to width ratio

PREFACE

For relevant information to be successfully applied to the definition of complex systems, the information must be known to exist and must be in a convenient form for ready application to the problem at hand. Direction from those individuals who maintain an expertise in the discipline is probably the most efficient and competent manner to apply existing knowledge to the definition of the problem; but the history of electro-optical system developments is fraught with those cases where nonspecialists were impressed into service to make specification, design and procurement decisions based upon the limited information available to them. As qualified individuals are developed in government laboratories and in industrial organizations, the substantial portion of the lack of competence problem at the working level will disappear. There will remain many individuals in various decision levels who are not familiar with electro-optical imaging systems, that will be making decisions that will influence imaging system design and procurement. Though these individuals may have access to excellent technical support, they may be prevented from successfully utilizing this support due to the absence of any technical grounding in the discipline.

Electro-optical, real time imaging systems were identified in a U.S. Army Missile Command Phase I Study* as an area where additional reference material would be of significant benefit in reducing specification and procurement problems induced by lack of competence at the various decision levels. Large amounts of material regarding imaging systems are already available, but it was clear from the Phase I study that the available information was not being used. Most of the information is dispersed and fragmented; and without a thorough grounding in the discipline, effective application of the material would be difficult. As a result of the Phase I findings, Phase II of the program was initiated with one of the goals being the generation of a document that would hopefully provide a coherent, comprehensive, readable over-view of the real time imaging problem for individuals with no assumed prior background in imaging system design or terminology.

*Asch, et al., Manufacturing Methods and Technology Study Covering Production and Inspection for Infrared Components, U.S. Army Missile Command, 1E-TR-70-1 (October 1970).

SECTION 1

INTRODUCTION

1.1 SCOPE

This document will limit itself to the treatment of three types of electro-optical sensor systems used in real time applications with a human observer as the interpreter of the imaged data. These sensors are television (emphasis on low light level), image converters (intensifiers or direct view devices), and Forward Looking Infrared (FLIR). The emphasis of the handbook is the military application of these systems although much of the material covered has general applicability.

1.2 PURPOSE

This document is concerned with providing a coherent overview to electro-optical imaging systems. This document should not be construed as an in-depth reference work, although some data and analyses are included where appropriate. The document may also be used as a checklist. The checklist concept brings to the evaluation of an imaging system an ordered, comprehensive reference against which the specialist and manager can compare system analyses and design for completeness.

1.3 ORGANIZATION

This document is structured for individuals with a technical background but with no particular experience in electro-optical imaging systems. The user is introduced to the subject in a very qualitative manner (Section 2) and is then introduced to fundamental concepts and terminology of real time, electro-optical imaging systems. The user is then exposed to the more detailed and quantitative aspects of real time electro-optical imaging systems and components thereof.

Section 2 is a qualitative description of the real time, electro-optical imaging problem. It introduces the user to system components and considerations which are covered in greater depth in Section 4.

Section 3 provides tutorial information on concepts and terminology which are essential to understanding the literature (and thus Section 4) of electro-optical imaging systems. This section is of the nature of an introductory text, and as such, most of the material is general in nature and is therefore not heavily referenced.

Section 4 is a logical development of the considerations that apply to the determination of an appropriate imaging system design. Section 4 considers observer requirements, system components, external factors such as atmoshere, and elementary system analyses. Section 4 is the most quantitative of all the sections and is heavily referenced for those individuals who wish to dig deeper.

SECTION 2

OVERVIEW

2.1 ELEMENTS OF THE REAL TIME IMAGING PROBLEM

2.1.1 General

The essence of the real time imaging problem is to use the available optical radiation (visible or infrared) from a target located in a background, which is also radiating, to form a usable image for an ovserver. Elements of a sensor system image the target radiation and convert it into an electrical signal which is processed to a form compatible with a selected display. This process is completed in a time frame which is very short compared to the observer's reaction time. The basic components of the problem are illustrated in Figures 2.1-1 and 2.1-2.

The imaging problem extends beyond the obvious elements in the information flow to include the observer's environment and limitations, mission determined parameters, and costs. Whether or not the observer can properly do his job includes such factors as viewing time available to him, display and/or observer motion (consider the situation of an observer in a tank on the move), fatigue and observer experience. The mission type may impose certain physical and performance constraints, such as portability for handheld devices or long range target detection for high performance aircraft, in defining the solution for a particular imaging problem.

2.1.1.1 Target and Atmosphere

Radiation from the target and background for imaging purposes comes from either reflection of incident light from radiation sources (such as the sun or artificial illumination) or self-radiation from the target and background themselves. The latter type of radiation, utilized by Forward Looking

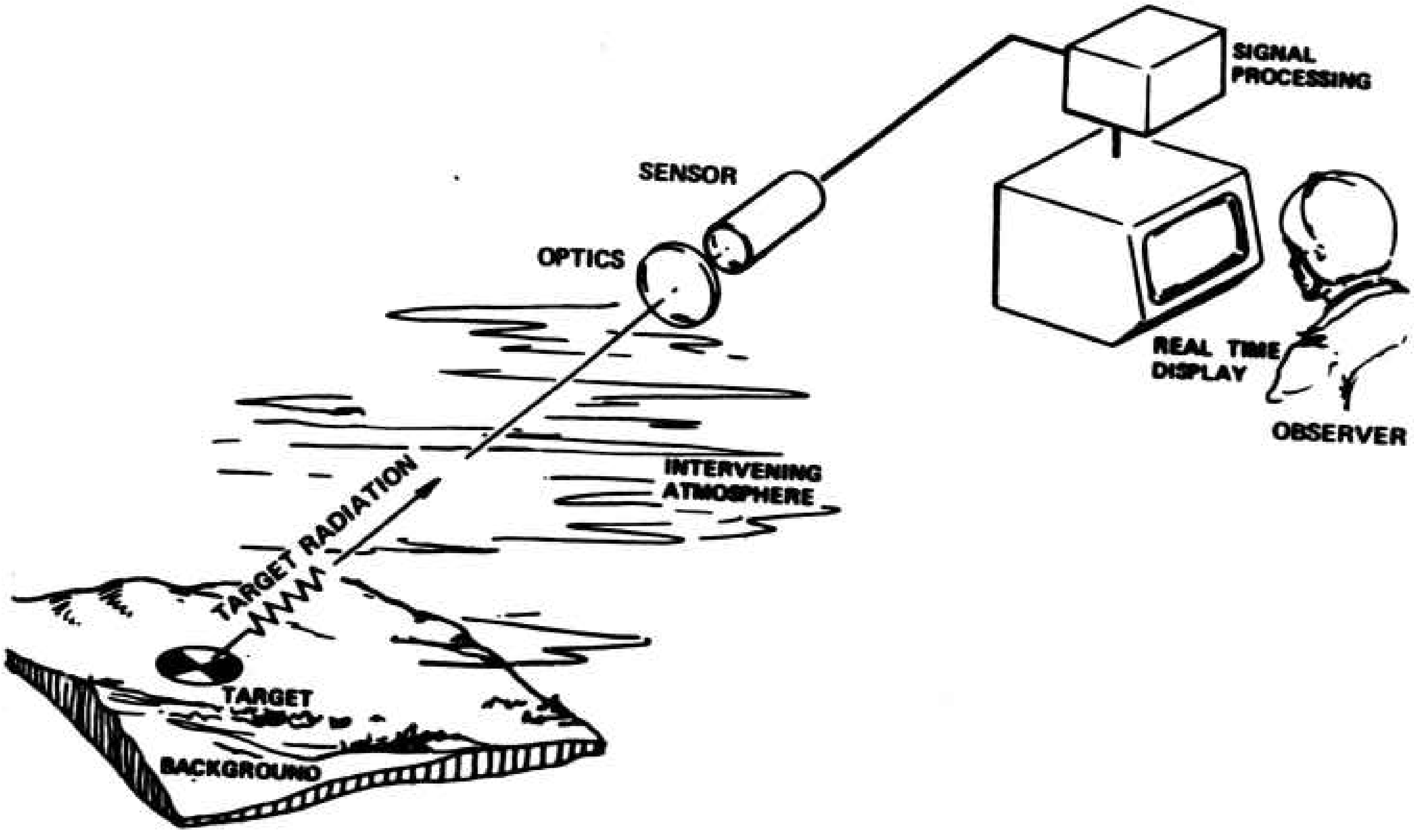

FIGURE 2.1-1. BASIC .LEMENTS OF THE REAL TIME IMAGING PROBLEM

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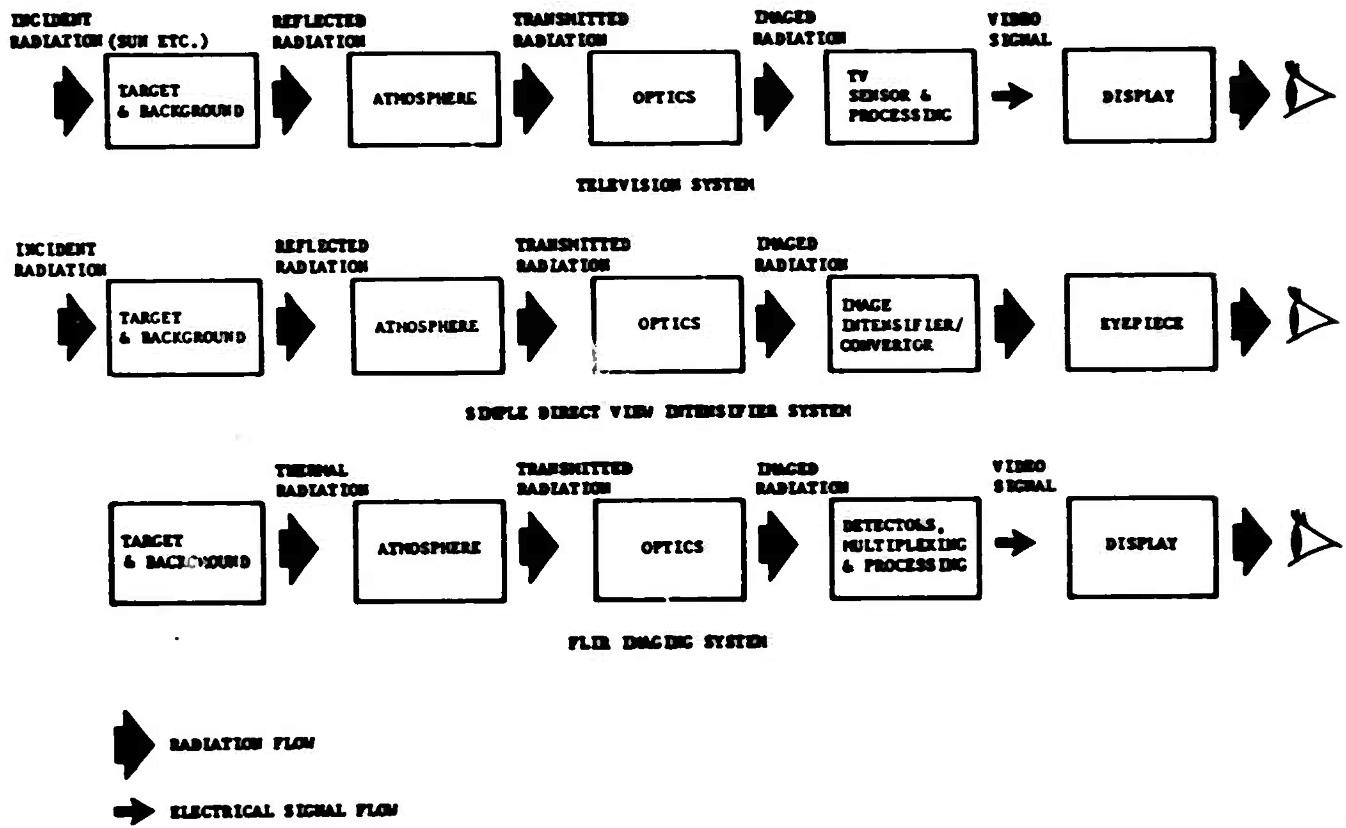


FIGURE 2.1-2. SIMPLIFIED BLOCK DIAGRAM OF INFORMATION FLOW IN THE REAL TIME IMAGING PROBLEM

Infrared (FLIR), results from the temperature of the imaged objects and is frequently termed thermal radiation. Television cameras and image converters use reflected radiation to form their images.

The atmosphere alters the radiant information by absorption and/or scattering and by adding to the target and background radiation additional radiation from other sources.

2.1.1.2 The Sensor System

The sensor (radiation transducer) system transforms the transmitted radiation information into an electrical analog signal, usually called the video signal, which can be used to construct an image on a display in a manner similar to a commercial television system. The direct view intensifier transforms the transmitted radiation into an observable image in the device itself. A separate display component is then not required.

The sensor system will consist of optics (lenses or mirrors) to image the received radiation, a photosensor (detector array, TV camera tube or image intensifier) located at the aforementioned image, processing electronics, and in some configurations a display.

2.1.1.3 The Displayed Image

All components in the image chain will modify the information of the initial target radiation. As such the displayed image is not an identical representation of the target in its environment. It is the intent of the system design to provide an image with sufficient information content and adequate quality to be usable to the observer.

2.1.2 ADVANTAGES OF AN IMAGING SYSTEM OVER THE EYE

2.1.2.1 Increased Radiation Gathering Capability

The human eye is limited to a maximum aperture diameter of 6mm (less than 1/4 inch) while aperture diameters of electro-optical systems are typically several inches and can be a foot or more. Since the amount of radiation gathered to form the image is proportional to the area of the aperture, some electro-optical systems can work effectively in situations where the eye is darkness limited. The image information obtained under low light level conditions usually can be displayed at a light level consistent with observer requirements.

Some electro-optical systems can have the additional advantage of being able to sense radiation in the infrared that is invisible to the human eye. This characteristic of electro-optical systems can be utilized to take advantage of transmission "windows" in the atmosphere (Section 3.1) and can provide an element of covertness where the target area must be artifically

illuminated (Paragraph 4.3.2.2). In the case of FLIR systems, thermal gradients in the target scene permit a visible image, representing the thermal gradient information, to be presented to this observer.

2.1.2.2 Magnification

The human eye is limited in its ability to resolve detail. In military applications the long detection ranges required will often result in the target's angular size being below the size threshold of the human eye. The threshold size is a variable and depends upon target characteristics and viewing conditions for the observer (Paragraphs 4.1.1 and 4.1.2). It is possible to increase the angular size of the target as it is viewed on the display by using the image forming optics and sensor to magnify the target scene and by increasing the display size. The degree of magnification is usually limited by physical considerations such as the size of the optics or tradeoffs with other optical system parameters such as field of view (the angular measure of the total scene being displayed.

2.1.2.3 Remote Location

Use of an electro-optical viewing system allows the flexibility to place an imaging sensor where it is inconvenient or dangerous to place a human observer and where observer vision may be obscured but is needed.

2.1.3 TYPES OF MISSIONS WITH REAL TIME IMAGING REQUIREMENTS

The following mission types are broadly described and should not be interpreted as being rigid mission definitions with definite imaging requirements for each type. The different mission types may dictate different imaging requirements which would be reflected in the imaging system design. In many cases a specific imaging system may provide sufficient flexibility to permit the displayed image to be useful for different mission types or alternatively, different phases of the same mission. Generally, this flexibility comes in the form of change in the field of view (magnification change) of the system which allows the operator to go from a search mode to recognition or attack mode after a target has been detected.

2.1.3.1 Navigation

A navigation display would give to the pilot (driver or helmsman) an image closely representing the "real world" and would cover a rather large field of view (Paragraph 4.4.1.3) of the terrain that the aircraft (vehicle) is about to enter. One should be most interested in realistically presenting broad geographic features (roads, rivers, etc.) of navigational interest in such a manner as to minimize disorientation of the pilot (i.e., the display should be referenced to the horizon).

2.1.3.2 Reconnaissance

Reconnaissance is generally taken to mean the detailed inspection of terrain to locate and identify resources of tactical interest. Because the information desired must be very accurate and the resources of interest (bridges, installations, etc.) are not usually mobile, high quality daytime imaging from nonreal time systems is preferred, although specific circumstances may require this information on a real time basis. Reconnaissance information is then used to prepare appropriate defensive and offensive plans such as briefed air strikes against specific targets.

2.1.3.3 Surveillance

Surveillance is concerned with what is happening at a given moment and the attempt is made to continually monitor activities of interest. In military applications the surveillance target is often mobile and action against that target must come from the information available to personnel in the surveillance vehicle. (This type of mission is also often referred to as armed reconnaissance.) There is therefore a strong requirement for real time imagery. The surveillance vehicle may be armed and free to attack to disrupt enemy support activities (interdiction).

2.1.3.4 Attack

The electro-optical system can also provide a display to allow night attacks or to provide a medium for actively guiding weapons. The emphasis of this mode is to provide detailed information about the target and a tracking aid at safe attack or standoff ranges. Normally this type of system would have smaller fields of view to attain the required high magnification.

2.2 OBTAINING THE OPTIMUM SOLUTION FOR A REAL TIME IMAGING SYSTEM

In addition to the constraints and boundaries imposed upon the imaging system by physics as discussed in Paragraphs 2.1.1 and 2.1.2; constraints of cost, schedule mission type and system interfaces will also impose boundaries upon the ultimate definition of an imaging system. Unless all the boundaries have been identified and well chosen, the resultant system design is likely to be less than optimum. One of the options that should remain open to the system designer is the freedom to perform design versus operational tradeoffs. Once the designer has received a closed ended specification many of the boundaries, realistic or otherwise, are already determined for him, and he will be limited to mere performance apportionment tradeoffs between system components. The freedom of the system designer to perform design/operational tradeoffs usually depends upon the phase or state of system development. Study and development phases should provide the designer as much latitude as possible.

By means of system analyses the system engineer or designer will apportion performance parameters consistent with mission requirements, costs and schedule (see Paragraph 4.7.1). Appropriate testing should be conducted to verify and define models and at appropriate stages of system development to verify the results of the system analyses.

When evaluating the performance of competitive systems or components, it is imperative that the analyst be aware of the assumptions and models involved in the analyses of the individual systems in order that he may make appropriate adjustments to put the expected performance results on a common basis.

SECTION 3

BASIC CONCEPTS

3.1 SPECTRAL CHARACTER

Subsection 3.1 is an introduction to the concept of spectral character as it applies to the imaging task. Perceived color is an example of spectral character, and this concept is extended to include optical radiation outside the range of human vision. The subsection includes discussion on the accepted models of light for describing the interaction of optical radiation with matter and on the spectral properties of light sources, the atmosphere and imaging system elements.

3.1.1 THE SPECTRAL NATURE

The sensation of color perceived by the human eye is related to the character of light known as wavelength, the physical measure of which is usually denoted by the lower case greek symbol λ. A change in wavelength of sufficient magnitude results in a change in perceived color so long as the wavelength is restricted to the range of wavelengths which are visually perceptible. This visible range of wavelength extends from violet (λ = 0.40 micrometer or 0.40 x 10^{-6} meters) to deep red (λ = 0.70 micrometer) for normal vision. The term "spectral" is the descriptive adjective which applies to effects of optical radiation which are dependent upon the specific value of wavelength. Specific distributions of light from radiation sources (such as lamps or the sun) as a function of wavelength are designated spectra. A spectrum may be continuous as in the case of the sun or a tungsten lamp or it may exist at discrete or specific wavelengths in which case it is a line spectrum (see Figures 3.1-1 and 3.1-2). The concept of spectra, spectral distributions, and spectral sensitivity (for optical radiation detectors) extends beyond visible radiation and is used

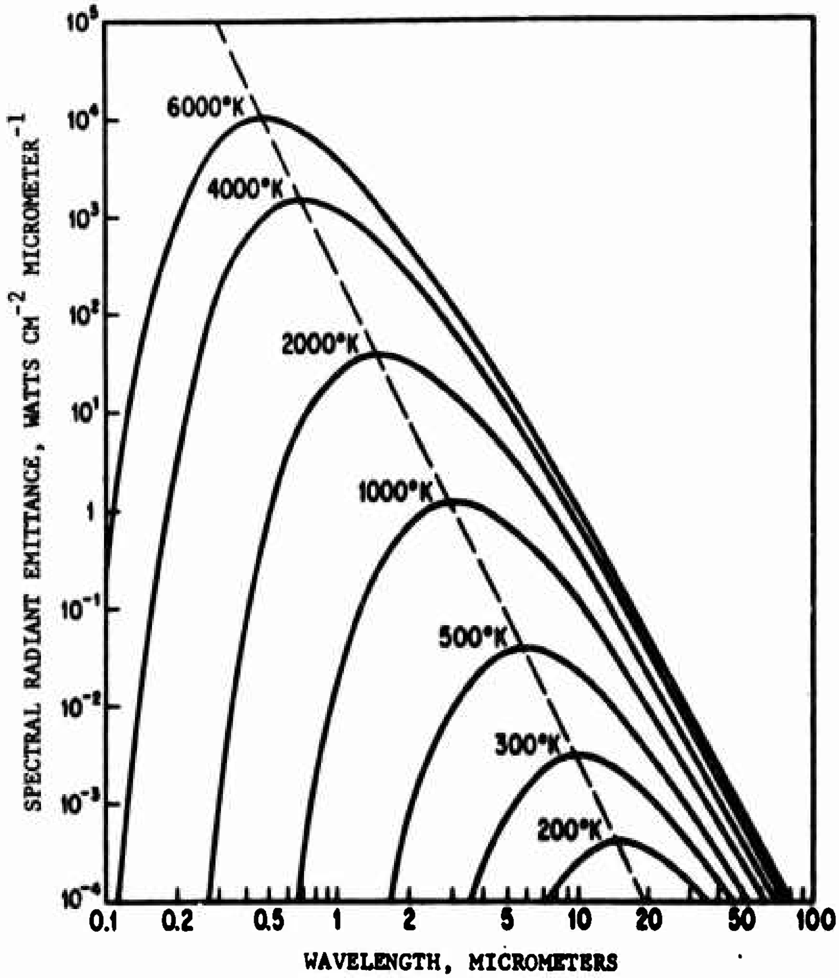


FIGURE 3.1-1. SPECTRAL RADIANT EMITTANCE OF A BLACKBODY AS A FUNCTION OF WAVELENGTH AT VARIOUS TEMPERATURES. MAXIMUM SPECTRAL RADIANT EMITTANCE AT A GIVEN TEMPERATURE FALLS ON THE DASHED CURVE (83).

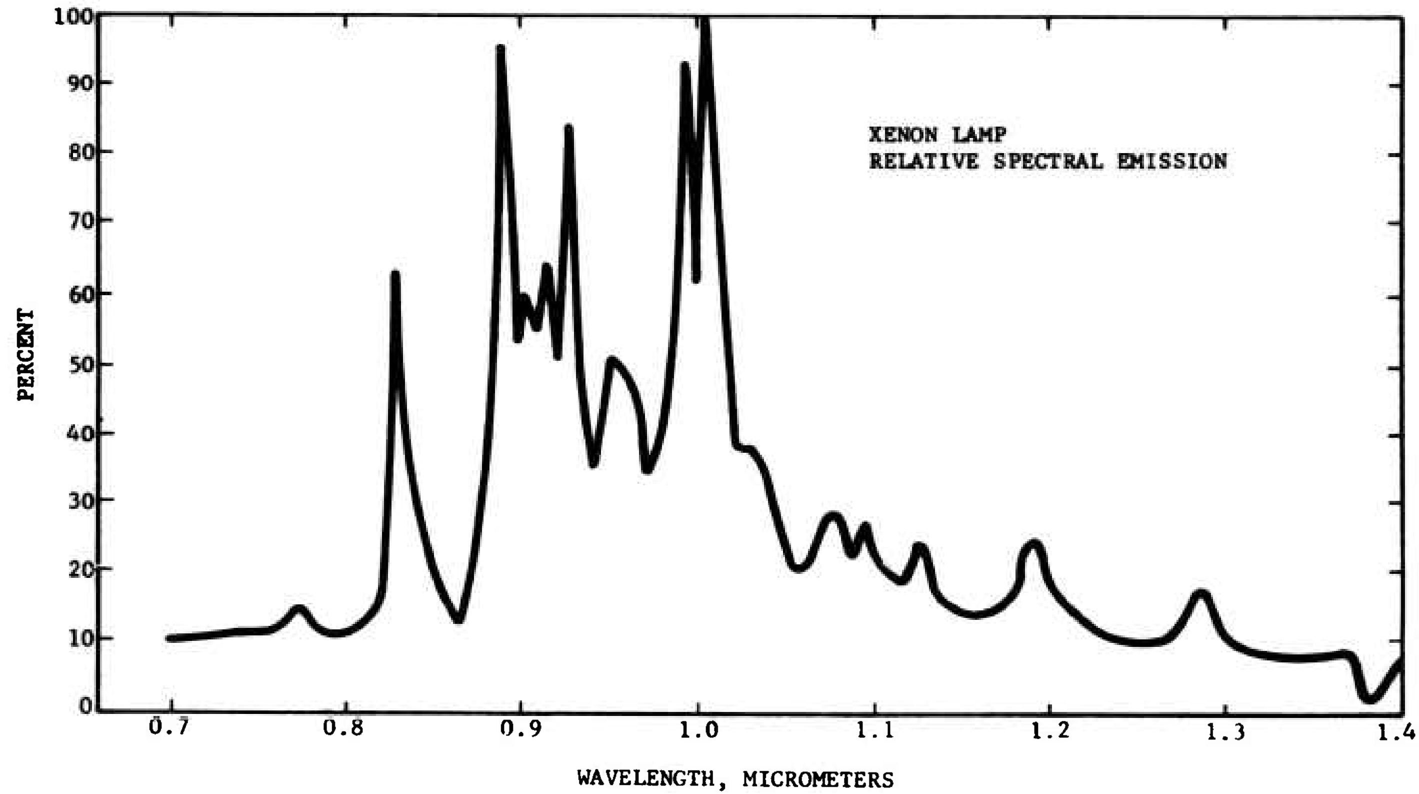


FIGURE 3.1-2. LINE SPECTRUM OF A XENON LAMP

in describing sources and detectors of optical radiation from X-rays and gamma rays ($\lambda = 10^{-10}$ meters) at shorter wavelengths to the far infrared ($\lambda = 10^{-4}$ meters) at longer wavelengths.

Wavelength is measured in metric units but several prefixes may be used. Micrometer (10^{-6} meters) is the most common unit for infrared radiation. Visible radiation is commonly measured in angstroms, nanometers or micrometers. Equivalence values of these units are found in Table 3.1-1.

TABLE 3.1-1

EQUIVALENCE VALUES OF COMMON MEASURE OF WAVELENGTH

	Micron (μ)* (10^{-6} meters)	Nanometer (10^{-9} meters)	Angstrom (10^{-10} meters)
1 Micrometer (10^{-6} meters)	1	1000	10,000

*This traditional unit is being deemphasized for current usage.

3.1.2 MODELS FOR DESCRIBING OPTICAL RADIATION

The nature of light and its interaction with matter cannot be satisfactorily described by a single model. Modern physics has accepted the necessity of describing light in terms of a dual nature. In some instances light behaves or is accurately described by a model which considers light to be a wave transverse to the direction of energy flow. In this model wavelength then describes the distance required to complete one cycle of vibration of the transverse wave; and as the speed of light in a vacuum is a constant for all wavelengths, wavelength is inversely proportional to the frequency of optical vibration. In this model energy is proportional to the square of the amplitude of the transverse vibration. (See Figure 3.1-3.)

The other model pictures light as particles or packets of energy called quanta. (See Figure 3.1-4.) If the light level is sufficiently low, the arrival of light quanta onto a sensing surface is described by statistical laws. This model is needed to explain the results of interactions of light with materials which free electrons when irradiated. The statistical nature of light can be seen by viewing a low light level scene with a low light level (LLL) imaging system where the noise or granularity in the picture is determined by the arrival rate of light quanta (see Paragraphs 3.4 and 4.1.2.4). The term wavelength (λ) is applicable in this model as a measure of the energy in each light quantum. The shorter the wavelength, the higher the energy in the light quantum. The relationship is

$$Q_{quantum} = h\,c/\lambda$$

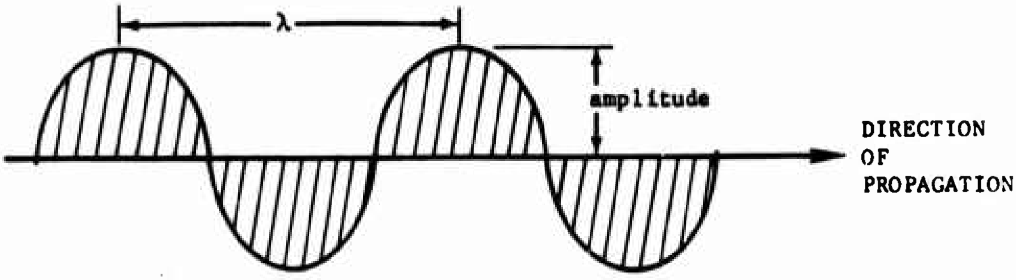


FIGURE 3.1-3. WAVE MODEL OF LIGHT

FIGURE 3.1-4. PARTICLE MODEL OF LIGHT

where c is the speed of light in a vacuum and h is a constant designated Planck's constant. Units are assumed to be consistent with the measurement system chosen (MKS, CGS). These two models are used to develop the "particle wave duality" of the nature of light.

3.1.3 SPECTRAL FILTERING OF ELEMENTS INTERACTING WITH OPTICAL RADIATION

Several elements in the real time imaging problem possess spectral transfer properties that modify the input optical spectrum. Parts of the spectrum will be relatively enhanced and other parts will be relatively suppressed. The normalized product of all the spectral modifiers (transforms) represents the relative effectiveness that each wavelength contributes to the image (see Figure 3.1-5) and consequently to the sensor electrical analog signal. The process of modifying the spectral content of an optical signal is termed spectral filtering, especially if the modification is deliberate in an attempt to provide a better image. When talking about a spectral quantity rather than an average value of that quantity over a broadband of spectral values, the symbol for the quantity is subscripted with the wavelength symbol λ. As an example the average reflectivity of a brick building to sunlight may be 30 percent ($\rho = 0.30$) but to the specific color yellow the reflectivity may be 40 percent ($\rho_\lambda = 0.40$ where $\lambda = 0.58$ micrometer).

3.1.3.1 Spectral Modification

If the target is imaged through reflected radiation, the reflected radiation will generally be of different spectral content than the incident radiation due to the spectral reflectivity of the target, ρ_λ (see Section 4.3). The atmosphere will selectively absorb and scatter radiation as a function of wavelength depending upon amounts and particle size of atmospheric constituents. Those portions of the spectrum where the atmosphere exhibits the least effect on the transmitted radiation are called atmospheric windows (Figure 3.1-6). The transmission of the optics preceding the imaging sensor is also a function of wavelength. In addition the imaging forming properties of refractive optics (lenses) are spectrally dependent leading to imaging errors called chromatic aberrations which must be corrected to acceptable limits (Paragraph 4.4.3.1). This arises from the differences in the speed of light in a dielectric medium, such as glass, as measured by the ratio of the speed of light in a vacuum to the speed of light in the dielectric (Figure 3.1-7). This ratio is called the index of refraction and is defined by

$$n_\lambda = c/v_\lambda$$

where v_λ is the speed of light in the dielectric medium (see Figure 3.1-7). The radiation transducer, whether the photocathode of a pickup tube or a quantum detector, will respond differentially to the spectral character of

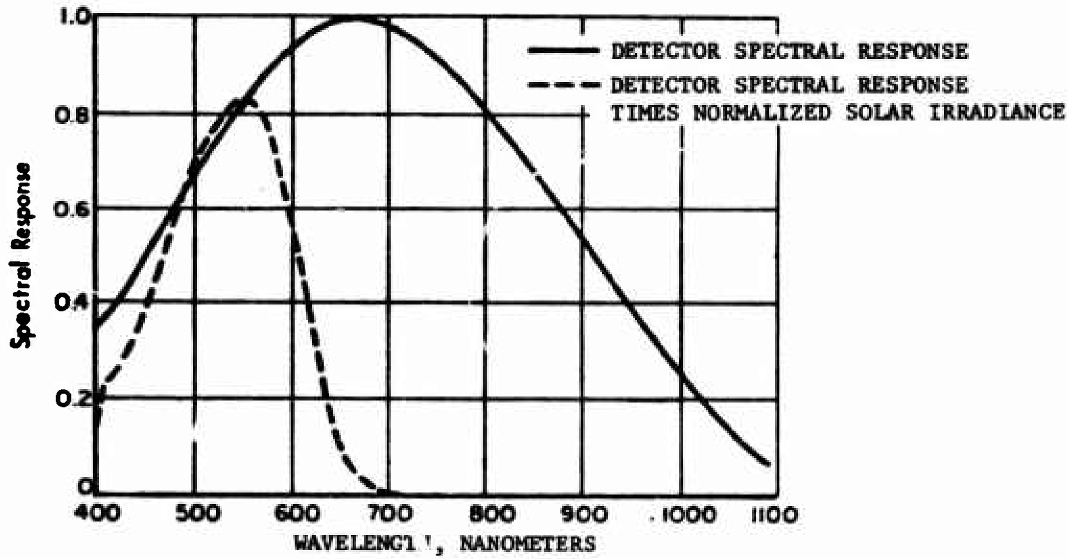


FIGURE 3.1-5. THE SPECTRAL RESPONSE OF AN S-1 PHOTOCATHODE AND ITS SOLAR IRRADIANCE PRODUCT (8)

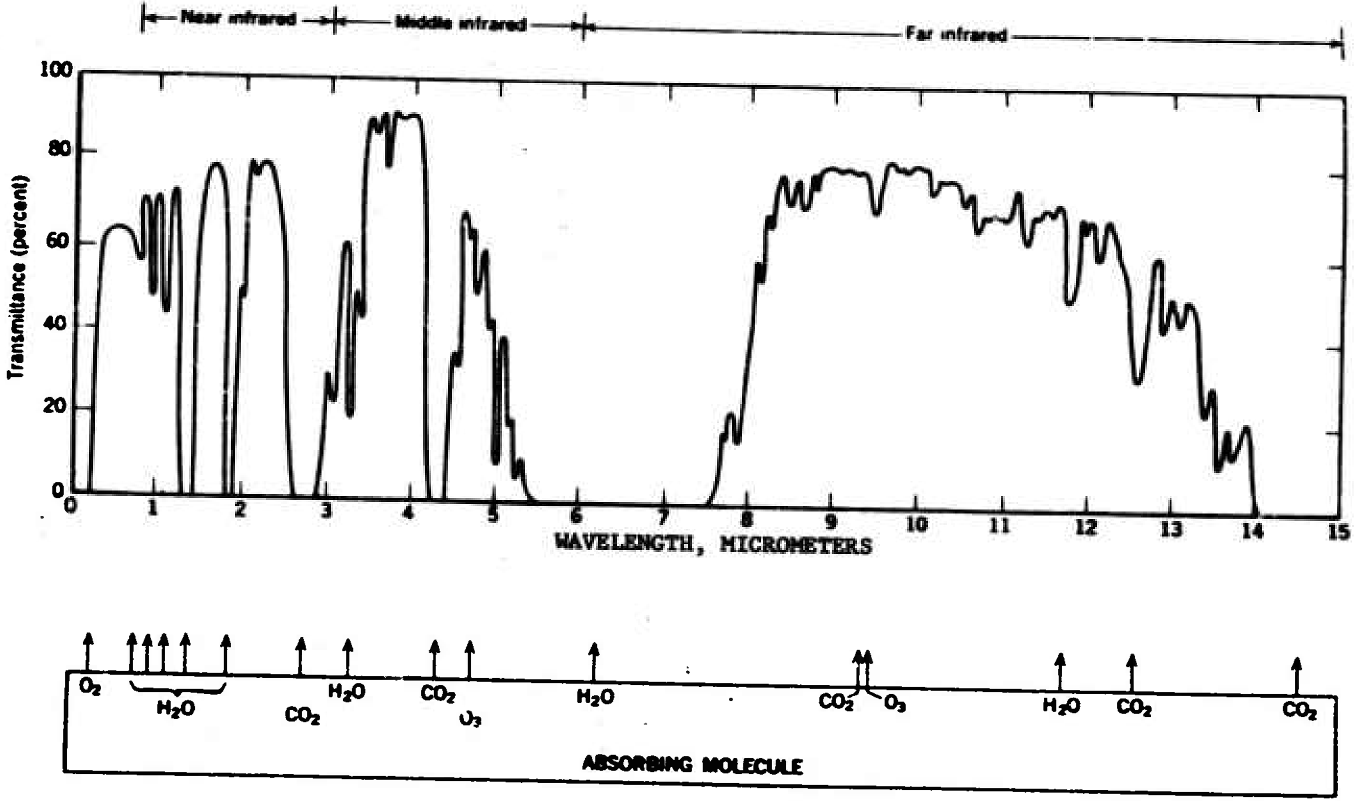


FIGURE 3.1-6. TRANSMITTANCE OF THE ATMOSPHERE FOR A 6000 FT HORIZONTAL PATH AT SEA LEVEL CONTAINING 17 MM OF PRECIPITABLE WATER (86)

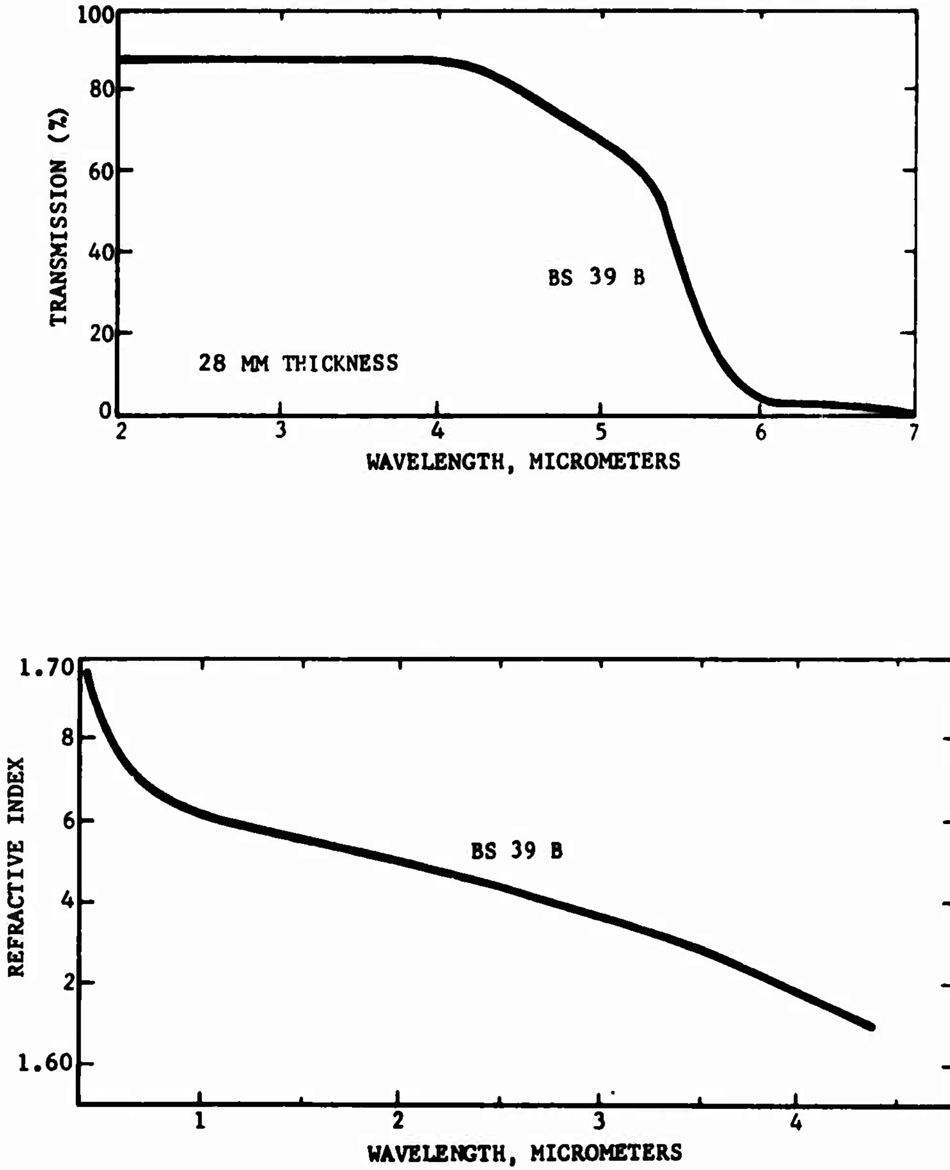


FIGURE 3.1-7. SPECTRAL PROPERTIES OF AN IR GLASS

the radiant image. The response of photocathodes is usually expressed in terms of spectral responsivity with units of R_λ amps/watt. (See Figure 3.1-8.)

3.1.4 The Blackbody and Spectral Emissivity

The concept of a spectrally variant output from a source has already been discussed (Figure 3.1-1). A blackbody is an optical radiator whose spectral radiant output is known from fundamental physical principles. The spectral radiant emittance* is described by Planck's law

$$M_\lambda = \left(\frac{C_1}{\lambda^5}\right)\left(\frac{1}{e^{C_2/(\lambda T)} - 1}\right) \text{watt cm}^{-2}\ \text{cm}^{-1} \qquad \text{(See Equation 4.3-16)}$$

where C_1, C_2 are constants, λ is wavelength and T is absolute temperature in Kelvins (K).

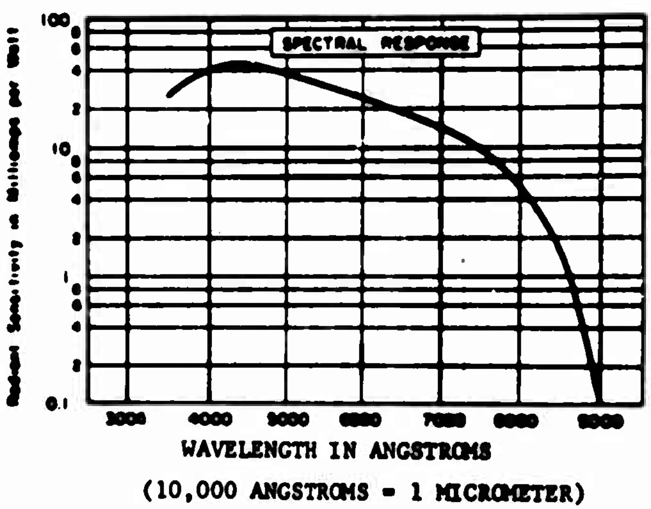


FIGURE 3.1-8. TYPICAL ABSOLUTE SPECTRAL RESPONSE CURVE FOR S-20 PHOTOCATHODE (23)

*See Appendix A for discussion of radiant terms. This law is sometimes expressed as a radiance in which case $L_\lambda = M_\lambda/\pi$.

The total radiant emittance from a blackbody over all wavelengths is found by appropriate integration of Planck's law and is

$$M_{BB} = \sigma T^4$$

where σ is the Stefan-Boltzmann constant.

The blackbody is the ideal thermal radiator by which other thermal radiators called gray bodies are compared for efficiency. The efficiency ratio on a spectral or wavelength to wavelength basis for radiators at the same temperature as the reference blackbody is called the spectral emissivity and it is designated ϵ_λ. ϵ_λ is always 1.0 for a blackbody and equal to or less than 1.0 but constant for a gray body. If ϵ_λ is variable with wavelength the radiator is said to be selective (Figure 3.1-9). The product $W_{\lambda BB}\,\epsilon_\lambda$ is used to describe a number of radiation sources including tungsten lamps, the sun and moon, and thermal targets for FLIR's.

3.1.5 Photometric Units

There are two systems, even sciences, of radiant measure. One science deals with all radiant energy with no special consideration for particular spectral bands and is called radiometry. The other science is a subset of radiometry and deals only with the radiation spectrum perceived by the human eye and is called photometry. Appendix A is devoted to a discussion of these two measurement systems as they apply to imaging systems.

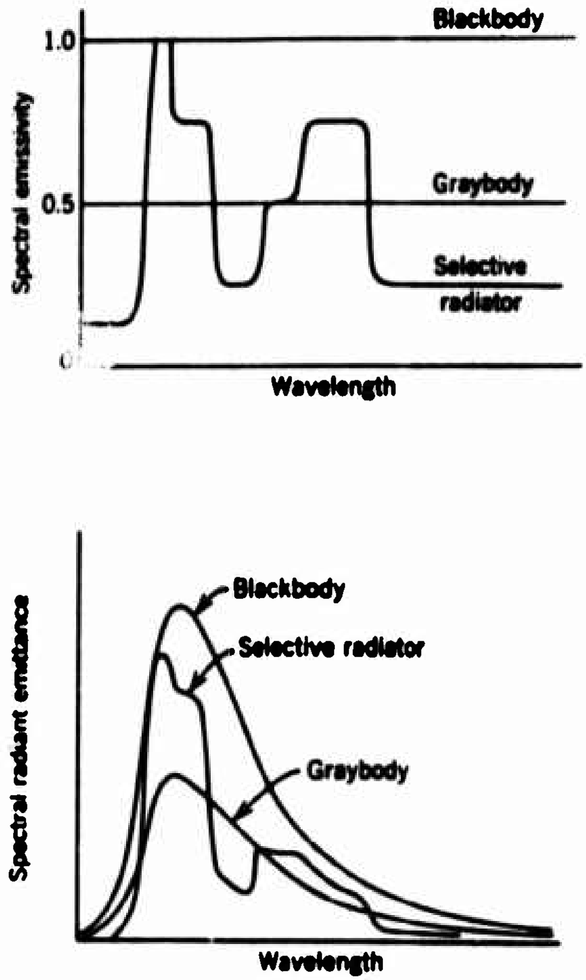


FIGURE 3.1-9. SPECTRAL EMISSIVITY AND SPECTRAL RADIANT EMITTANCE OF THREE TYPES OF RADIATORS (86)

3.2 CONTRAST

Subsection 3.2 is an introduction to the concept of contrast. In a qualitative manner it describes the physical basis for the generation of contrast, and in a similar manner describes the change in contrast resulting from transmission through the atmosphere and through the elements of the imaging system. It also introduces the subject of observer requirements as they relate to contrast.

"Man's ability to see objects through the atmosphere, underwater, or in space by naked eye or with the aid of magnifying or filtering devices is limited by the availability of light, its distribution on the object of regard and its background, the reflective properties of both, the image transmission characteristics of the intervening media, the properties of any magnifying and filtering devices employed, and the characteristics of the human visual system." This statement introduces the collection of papers comprising the "Visibility" issue of Applied Optics (87).

"If a completely uniform and infinitely extended surface is presented to the eye, no sensations other than those of luminosity and color are produced. . . . Most of the information about our world which we obtain through our sense of vision depends upon the perception of differences in luminance or chromaticity between the various parts of the field of view. An object is recognized because it has a different color or brightness from its surroundings, and also because of the variations of brightness or color over its surface. The shapes of things are recognized by the observation of such variations." Middleton thus begins Chapter 4 of his book "Vision Through the Atmosphere" (31).

With suitable modifications, the above statements are also applicable to viewing with electro-optical image forming systems. The "signal" generated in such a system arises from the differences in spectral radiance between various parts of the viewed scene. In the visual spectrum most objects are seen because they reflect incident light, the brighter objects reflecting more light than darker objects. Incandescent objects are seen by virtue of the visible radiation they emit. The visibility of an object is a function of the signal, or spectral radiance difference between the object and its background. This function of spectral radiance difference is usually referred to as "contrast." Some commonly used specific definitions of contrast are given in Paragraph 4.3.3.2.

Most low light level TV systems employ sensors having an "extended red response." They respond to radiation not only in the visual spectrum but also in the near infrared spectrum (IR), out to 0.8 or 0.9μm for the more sensitive photoemitters, and to beyond 1.0μm for the less sensitive photoemitters and photoconductors. In this spectral region most objects are

seen because of reflected radiation, just as in the visual spectrum, but contrasts can be much different, sometimes even being reversed, from the visual. Vegetation containing chlorophyll is highly reflective in the near IR so that trees, especially deciduous trees, appear quite bright. Therefore visual contrasts generally cannot be used in estimating the performance of a low light level sensor.

Forward looking infrared (FLIR) sensors generally operate in one of two atmospheric windows, either the 3 to 5μm band or the 8 to 14μm band. At these wavelengths, the radiance due to self-emission is greater than that due to reflected flux (see Paragraph 4.3.3.3). Thus the signal used to generate the FLIR image is due to the difference in radiant emittance between various parts of the scene. This signal can arise from small temperature differences between scene elements, or from emissivity differences or both. The statement is often made that, because FLIR sets (systems) sense self-emitted rather than reflected radiation, their operation is not dependent upon a source of illumination. This statement is not entirely true because the sun heats objects up to different temperatures during the day. These same objects cool at various rates in the absence of the sun. Consequently the "contrast" at FLIR wavelengths changes continually during a 24-hour period. Other factors, such as wind, rain, or heavy dew can also substantially affect FLIR signals.

It is common experience that distant objects can sometimes be seen and sometimes not, depending upon "the visibility." The <u>inherent luminance</u> or radiance of an object is defined as the luminance or radiance which would be measured in the absence of an intervening atmosphere. The <u>apparent luminance or radiance</u> of an object is that which is measured when the object is viewed through an intervening atmosphere. The inherent radiance of an object is affected in two ways. First, the atmosphere attenuates the flux that should reach the observer by scattering it out of the path and by absorbing it. Secondly, the atmosphere scatters flux into the path so that it arrives at the observer as if it had originated at the object. Thus a black object which has zero inherent luminance appears lighter and lighter as it is viewed at a greater distance. Brighter objects appear darker and darker as they are viewed from a greater distance. Finally, all objects assume the luminance of the horizon sky as they are viewed beyond the range of visibility.

What this means is that the signal available to the EO sensor is diminished by the atmosphere. This subject is treated quantitatively in Paragraphs 4.3.3.2 and 4.3.3.4.

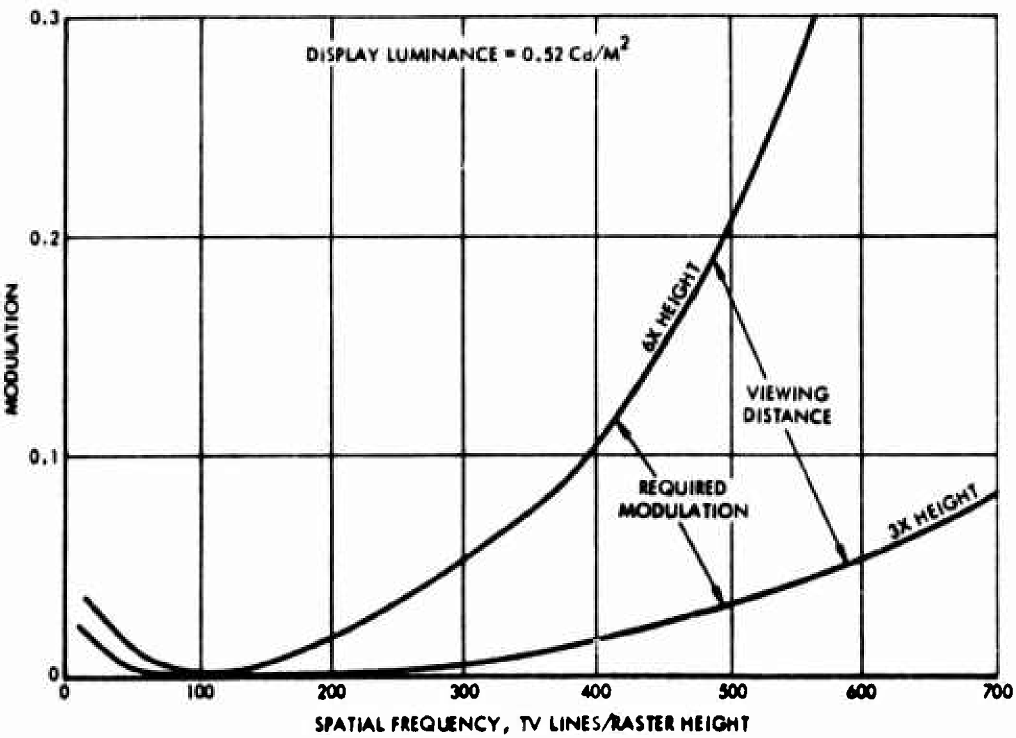
The atmosphere is not the only agent that reduces the signal. The contrast of small objects or scene details is reduced in the EO sensor itself, so that the contrast of the displayed image will be less than that ideally expected. This can be illustrated by using the objective lens as an

example. Any real lens is incapable of imaging a "point." The image of the "point" will have a finite size, or blur spot, which is determined by the aberrations and diffraction of the optical system (see Paragraph 4.4). Likewise, targets whose image is small compared to the optical aberration will also be spread. This means that the peak signal which should have been produced from the apparent radiance difference between the target and its background is reduced since the fixed amount of flux is spread over a greater area. This degradation occurs, to a greater or lesser extent, in each component of an imaging system. Thus, for example, the addition of image intensifiers to a TV camera will increase its sensitivity, but only with an attendant loss in contrast rendition for small detail. This is usually expressed as a "loss in resolution." Resolution and the relationship between resolution and image quality is discussed in Paragraph 3.3.

It is common to talk of the magnification of an EO imaging system. For example, if a real target subtends 5 milliradians if viewed with the unaided eye, and 35 milliradians if viewed on the EO display (at some nominal viewing distance), the system is said to have a magnification of 7. The viewing quality of the EO system with a magnification of 7 will generally be nowhere near comparable to that produced by a pair of 7 power (magnification of 7) binoculars in daylight. This is because the contrast rendition of the EO system, with its many more components, is usually significantly poorer than that of a pair of binoculars (i.e., the resolution capability of the EO system is much less than that of the binoculars).

It is obvious that there must be a requirement for some minimum value of contrast presented to the observer, if he is to be able to discern the displayed image of a given target. In the case of TV systems, the usual standard target is a bar pattern (see Paragraph 3.3), and the limiting resolution (see Paragraph 3.3) has been taken to be the spatial frequency at which the contrast (see Paragraph 4.3.3.2) has been reduced to a somewhat arbitrary value. It is assumed that the type of contrast is TV contrast (see Paragraph 4.3.3.2) in the displayed image, defined by Equation (4.3-10). The minimum contrast is usually chosen to be between 2 percent and 10 percent. In general, if optical bar patterns are imaged with an EO system, the peak-to-peak signal output will decrease with increasing spatial frequency (see Paragraph 3.3). That is, contrast rendition for higher spatial frequencies is reduced. This is akin to the concept of contrast reduction for small targets, introduced above.

A slightly more sophisticated approach is coming into general usage to describe the minimum contrast requirement. It recognizes that the contrast required for discernment is a function of the display brightness, as well as the angle subtended by the target. The result is a curve of observer contrast requirements called the demand modulation function, or DMF. (Modulation is a specific kind of contrast ratio and the concept of contrast as introduced in Paragraph 3.2 applies.) An example is shown in Figure 3.2-1. This subject is covered further in Paragraph 4.1.1 of this report.



1. SEE APPENDIX A FOR A DISCUSSION OF LUMINANCE AND ITS UNITS
2. SEE 3.3 FOR DISCUSSION OF SPATIAL FREQUENCY

FIGURE 3.2-1. REQUIRED MODULATION FOR VIEWING DISTANCE EQUAL TO 6 AND 3 TIMES RASTER HEIGHT (7)

3.3 RESOLUTION AND MODULATION TRANSFER FUNCTION

Subsection 3.3 introduces the concepts of resolution and limiting resolution. These are the traditional terms of describing imaging system performance. Concepts of spatial frequencies are introduced. The more complete method of evaluating system performance is the Optical Transfer Function (OTF) and its modulus the Modulation Transfer Function (MTF). The OTF (MTF) concept is introduced and discussed including when OTF methods apply and are practical. The relationship of MTF and image quality is also discussed.

3.3.1 RESOLUTION AND LIMITING RESOLUTION

The term resolution or resolving power relates to the ability of an imaging device (including the eye) or system to produce separate images of objects very close together. Figures 3.3-1 and 3.3-2 figuratively illustrates the concept. When the resolving power is limited by diffraction effects in the optics (Paragraph 4.4.3.2) and the images are barely resolvable as in Figure 3.3-2c, then one is discussing "Rayleigh's criterion" for resolution.

Resolution is one of the traditional measurements of evaluating the image forming capability of an optical system. The usual method is to observe the image formed by the system from a test chart as the otserved object.

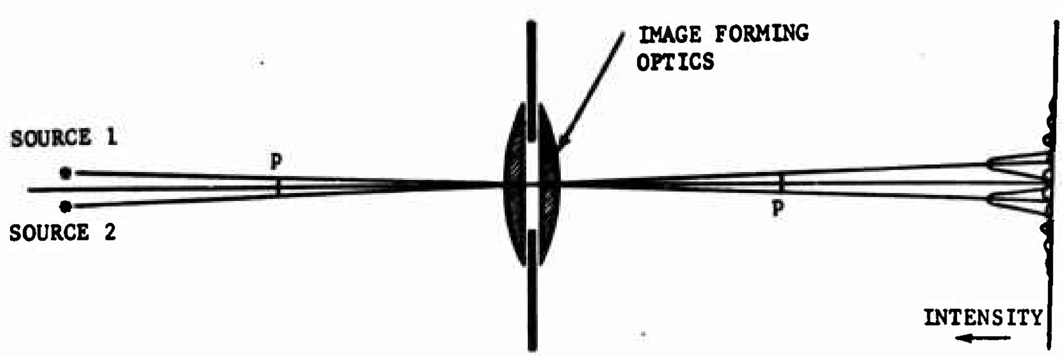


FIGURE 3.3-1. DIFFRACTION IMAGES OF TWO SLIT SOURCES FORMED BY A RECTANGULAR APERTURE (79)

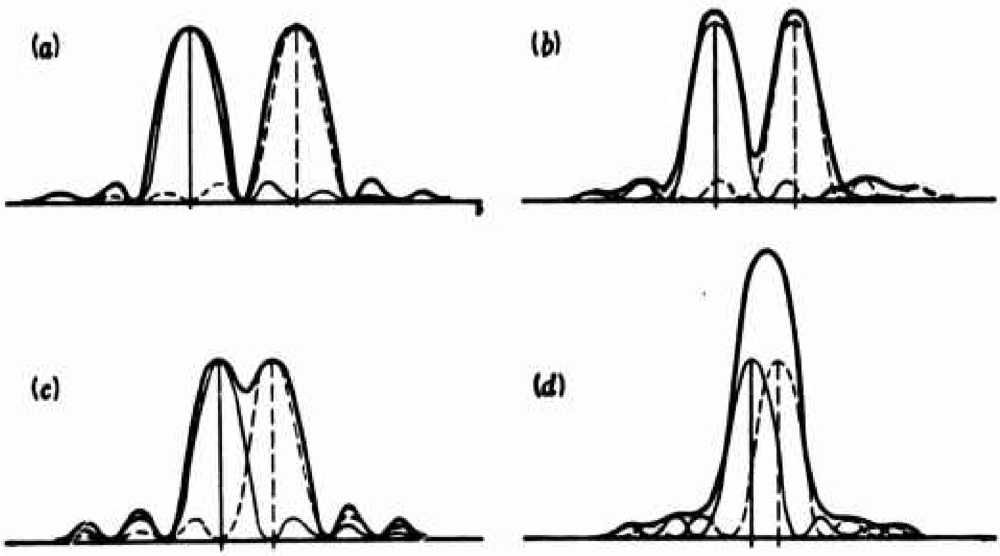


FIGURE 3.3-2. DIFFRACTION IMAGES OF TWO SLIT SOURCES. (a) COMPLETELY RESOLVED (b) WELL RESOLVED (c) JUST RESOLVED (d) NOT RESOLVED (79)

There are a number of standard test charts with wide acceptance (Figures 3.3-3, 3.3-4) depending upon the type of system and component to be evaluated. They are generally bar charts of high contrast. The variation is usually in the arrangement of the bars, number of bars in the group and the length to width ratio of the bars. The limiting resolution is that portion of the pattern where the modulati ' of the pattern in the image can be just discerned. Depending upon the use of the component (system) and the radiant spectrum, the detector for observing the image pattern can be the unaided or aided (auxiliary optics for magnification) eye or a radiation detector. The units for limiting resolution depend upon the chart used and component being evaluated. As an example limiting resolution for optics is generally expressed in bar cycles per linear dimension in the image plane (cycles/mm or line pairs/mm) while for a television system it is the number of lines (1 bar cycle equal 2 TV lines) in a frame height. For television sensors it is common to determine the limiting resolution versus light level as a measure of the low level capability of the sensor system

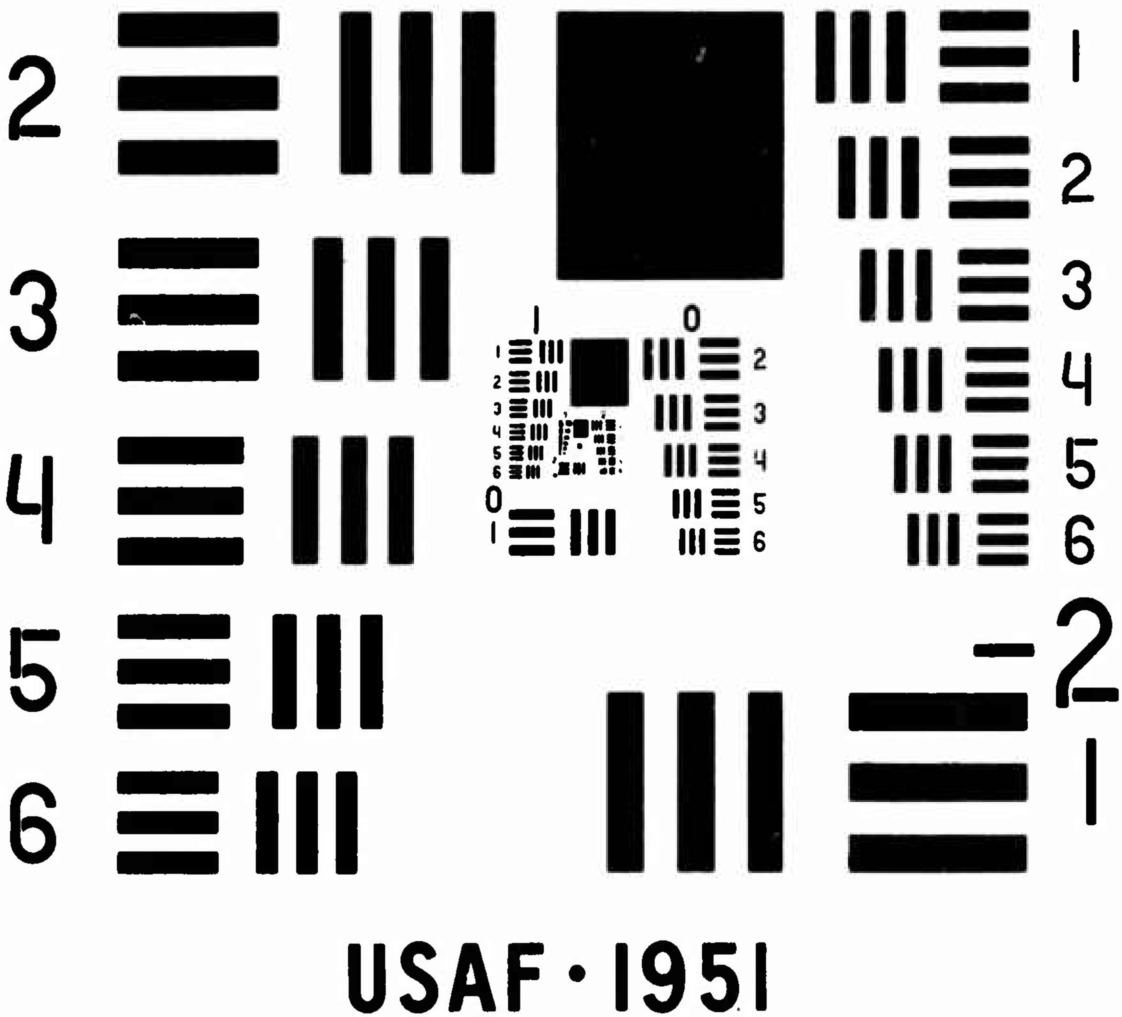


FIGURE 3.3-3. USAF THREE BAR RESOLUTION PATTERN

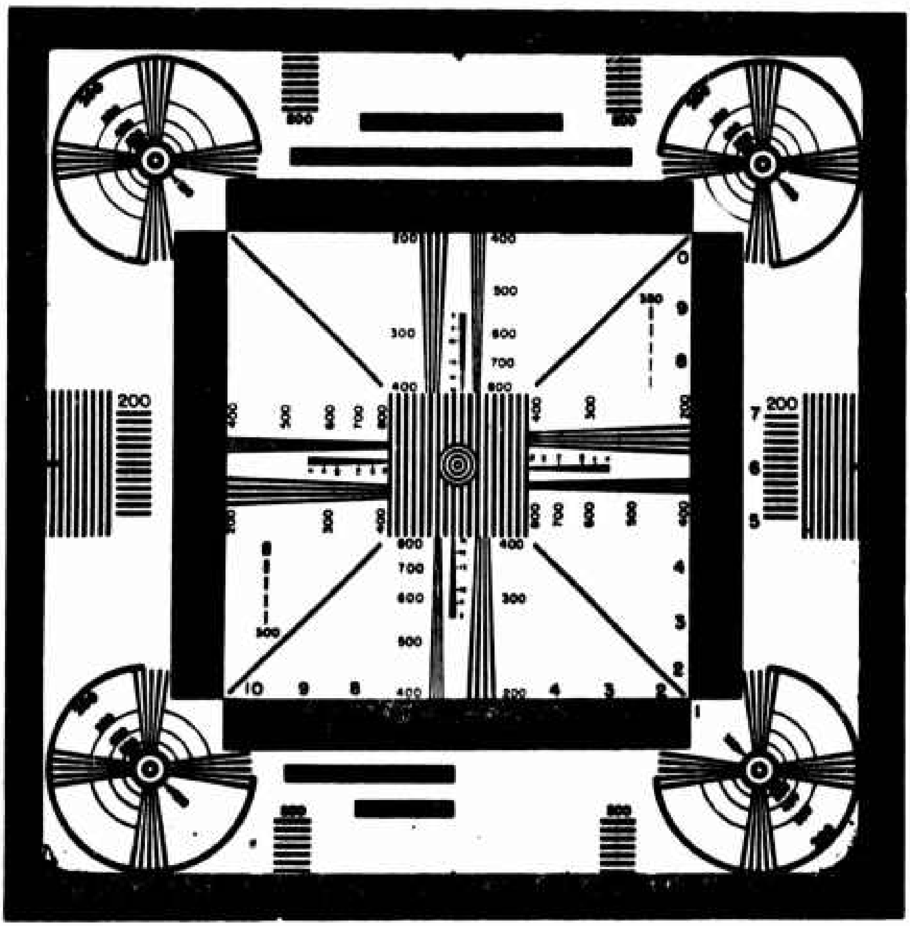


FIGURE 3.3-4. RETMA CHART

(Paragraphs 4.5.3.1 and 4.5.3.2). The use of limiting resolution as a valid measure of imaging performance is being replaced by MTF concepts (Paragraph 3.3.3) because limiting resolution tells nothing about the imaging performance and contrast transmission characteristics of systems for images larger than the one representing the limiting resolution.

3.3.2 RESOLUTION TERMI. .OGY AND INTERRELATIONSHIP

The base unit for describing optical resolution is the optical cycle which for a bar chart includes the pair consisting of a black and white bar and for an MTF target is the cycle of an intensity sine wave as illustrated in Figure 3.3-5. The sine wave target can be considered proportional to the fundamental of the square wave or bar target of the same period. Because the black and and white bar represent a pair it is common to refer to an optical cycle of a bar chart as a line pair. In the case of television each half of the optical cycle is considered a resolution element and is assigned the value of a line of resolution; hence, one optical cycle is

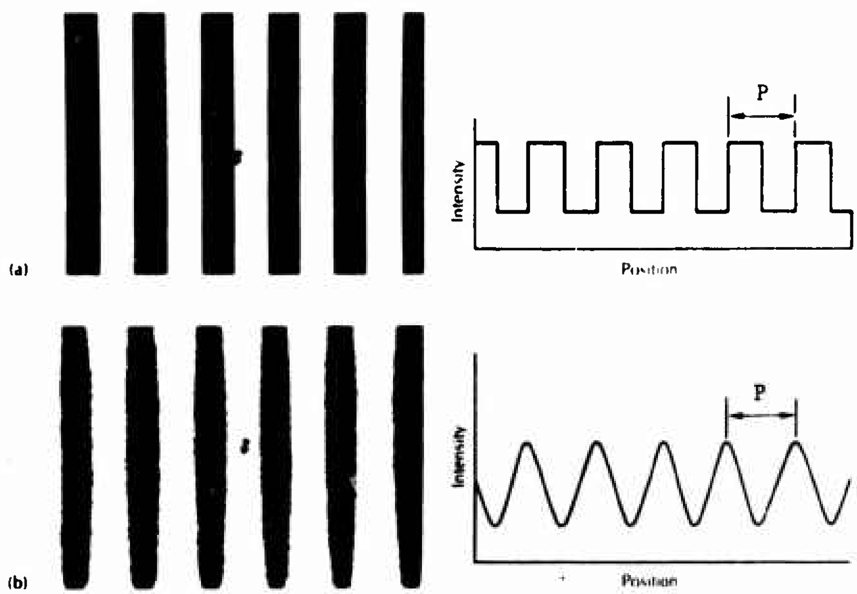


FIGURE 3.3-5. PERIODIC INTENSITY PATTERNS (a) SQUAREWAVE, (b) SINE WAVE

equal to two TV lines in subtense. TV lines of resolution should not be confused with the number of scan lines displayed on a cathode ray tube. Resolution may be a function of the number of scan lines, but the units describe different system variables (see Paragraphs 4.2.2.2 and 4.7.3.1).

The common measures of resolution performance are cycles per unit length, cycles per unit angle, or cycles per field of view or frame height. Cycles per unit length are usually used with image plane evaluation of optical systems or photocathode resolution performance.

$$\nu_{image} = \frac{\nu_{object}}{M}$$

where M is the magnification of the optical system and ν is usually cycles (line pairs) per millimeter.

Occasionally the inverse of this relationship is used in which case the dimensions are expressed in millimeters per line pair. At times it is more meaningful to express resolution in angular terms than linear ones. One such time is when resolution in the field of view (see Paragraph 4.4.1.3) is desired but varying target range precludes a single expression of resolution in linear terms. The angular resolution can be expressed as a function of the focal length (Paragraph 4.4.1.2) of the optical system when the image plane linear resolution ν_{image} is known The relationship is

$$\psi = \nu_{image} f$$

where f is the focal length of the optics in millimeters if ν_{image} is in line pairs per millimeter. The object is assumed to be at infinity (the object distance is much, much greater than the focal length). The units of ψ are in line pairs per radian. It is more common to express ψ in units of line pairs per milliradian in which case the relationship is changed as follows.

$$\psi = \nu_{image} f/1000$$

A common unit for limiting resolution is the maximum number of resolution elements that can be resolved in a frame dimension (usually the frame height). (A frame is the area occupied by the image of the scene, i.e., the active area of the photocathode and/or the displayed picture.) The resolution element normally used is the TV line. The limiting resolution of a frame is then

$$N_{TV\text{-}limiting} = 2\nu_{image\text{-}limiting} \quad 1$$

where d is the linear dimension of the active portion of the photocathode in millimeters if ν_{image} is in line pairs per millimeter. N_{TV} is in TV lines per frame height (if d is the height).

3.3.3 CONCEPTS OF SPATIAL FREQUENCIES - OTF AND MTF

3.3.3.1 Spatial Frequency

If one were to scan an infinitely small detector across the scene, he would get an electrical signal representing the intensity or reflective contours of the scene (Figure 3.3-6). The waveform of that signal is representable by a superposition of sine and cosine waves of varying frequency, amplitude and phase known as a Fourier spectrum. Each of the specific components (i.e., the single frequency with its amplitude and phase) of the series is known as a Fourier component. As the electrical signal can be described by a Fourier synthesis, so can the scene itself be described by a Fourier spectrum. The units for the scene or spatial spectrum are cycles per linear dimension. The frequency of each of the Fourier components then represents the spatial frequency of that part of the scene. The detector output of a scan of a periodic bar chart would appear the same as the function in Figure 3.3-5 with time as the abacissa instead of position. If P is the period of that bar chart the periodic frequency is $\nu = 1/P$ (units are cycles per dimension of P). The Fourier components or spatial frequencies for that wave train exist at odd harmonics of the ν frequency and they are:

Fundamental or first harmonic $$g(\nu) = \frac{4}{\pi} A_{sq} \sin\left(\frac{1}{P}\right)$$

Third harmonic $$g(3\nu) = -\frac{4}{3\pi} A_{sq} \sin\left(\frac{3}{P}\right)$$

Fifth harmonic $$g(5\nu) = \frac{4}{5\pi} A_{sq} \sin\left(\frac{5}{P}\right)$$

etc., where A_{sq} is the amplitude of the square wave radiance, $g(n\nu)$ is the trigonometric function comprising the Fourier component. Figure 3.3-7 demonstrates the superposition of this simple, discrete (as opposed to continuous) Fourier spectrum into a periodic square wave by combining the Fourier components of proper amplitude in proper phase. The frequency spectrum of a periodic pattern such as a bar pattern or a sine wave pattern is relatively simple compared to the spectrum of a complex scene. With respect to resolution chart bar patterns as discussed in Paragraph 3.3.1, it should be noted that groups of bars will have a different frequency spectrum than does a continuous periodic function of the same spacing. As a consequence, a 4-bar target will give a different limiting resolution

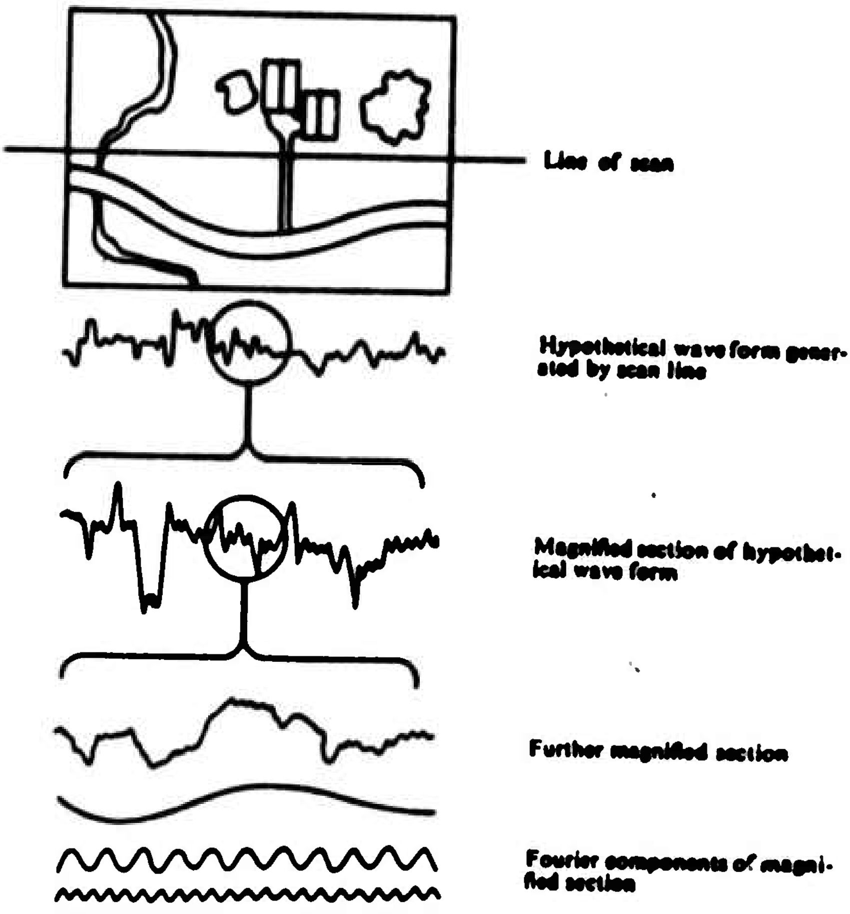
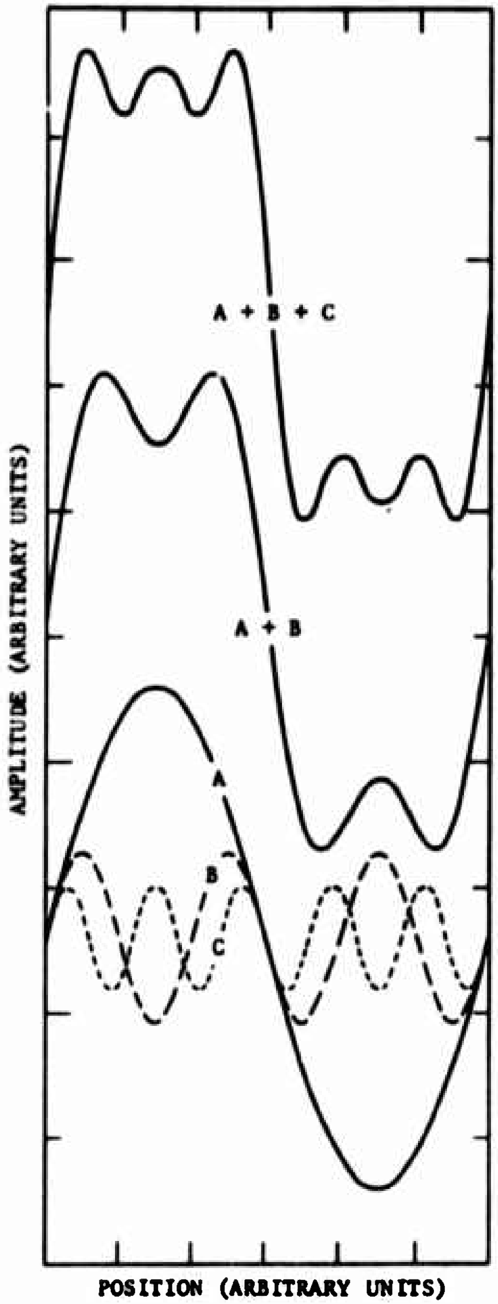


FIGURE 3.3-6. SPATIAL SINE WAVE ANALYSIS (10)



THE ADDITION OF SINE WAVES TO SYNTHESIZE A SQUARE WAVE. WHEN THE FREQUENCIES OF THE SINE WAVES ARE ν, 3ν, 5ν, 7ν,...., AND THE CORRESPONDING AMPLITUDES ARE A, 1/3A, 1/5A, 1/7A,...., THE SUM OF MORE AND MORE SUCH WAVES APPROACHES A SQUARE WAVE MORE AND MORE CLOSELY. ($A = 4/\pi\ A_{sq}$)

FIGURE 3.3-7. SINE WAVE SYNTHESIS TO FORM A PERIODIC SQUAREWAVE (6)

than that given by a 3-bar target or a RETMA* chart. While it is valid to treat radiant distributions as having a single linear dimension when discussing a line scanning system, the human eye senses radiant distributions two-dimensionally and its ability to detect limiting resolution is a complex interaction of the spatial distribution in both directions. For this reason the length to width ratio of the bar pattern will also affect the limiting resolution value (Paragraph 4.1.2).

3.3.3.2 Optical Transfer Function (OTF) and Modulation Transfer Function (MTF)

The OTF is a measure of the manner in which spatial frequency information is transmitted through an imaging component or system. The OTF is a complex quantity and consists of a real and an imaginary part. The OTF is represented in polar form by the product of the modulus and an exponential term which are spatial frequency dependent. The modulus describes the amplitude or modulation transmission and is called the MTF. The argument of the exponential term is called the Phase Transfer Function (PTF), and it describes the phase relationship of the transmitted frequencies. (See a text such as (124) for a mathematical treatment of the OTF.)

Figures 3.3-8 and 3.3-9 depict the nature of the MTF and PTF by consideration of what happens to the spatial information contained in a test target consisting of a sinusoidally varying intensity pattern. Figures 3.3-9a and b demonstrate the decrease in modulation with higher spatial frequencies. If a sufficient number of frequencies are measured, the response of the system is determined and the response curve is plotted in a manner similar to Figure 3.3-9e. One may also expect a relative shift of position of the component frequencies in the image plane from that in the object plane and this is demonstrated in Figure 3.3-9c and d. The amount of shift can be related to a phase angle and plotted as in Figure 3.3-9f.

The OTF can be defined precisely in mathematical terms using the Fourier transform and the line spread function (LSF). The OTF (or MTF) is

*The RETMA chart is defined by EIA (Electronic Industries Association) Standard RS-170. RETMA derives from the prior name of the EIA, the Radio-Electronics-Television Manufacturers Association.

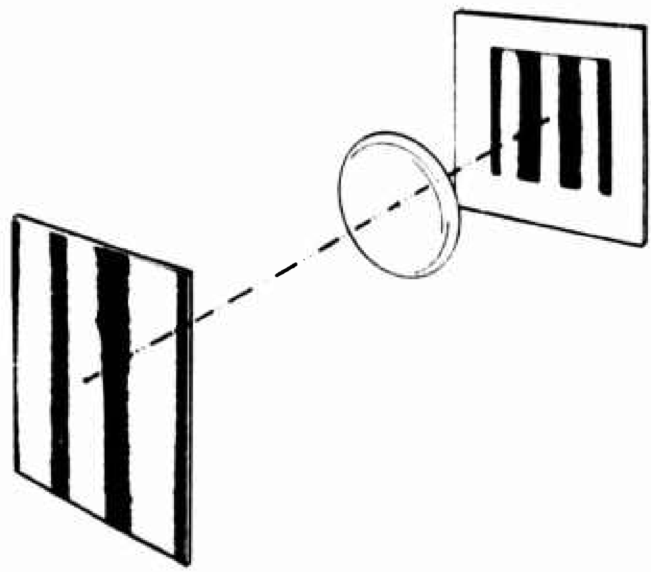


FIGURE 3.3-8. LENS FORMING AN IMAGE OF A PERIODIC SINE WAVE TEST PATTERN

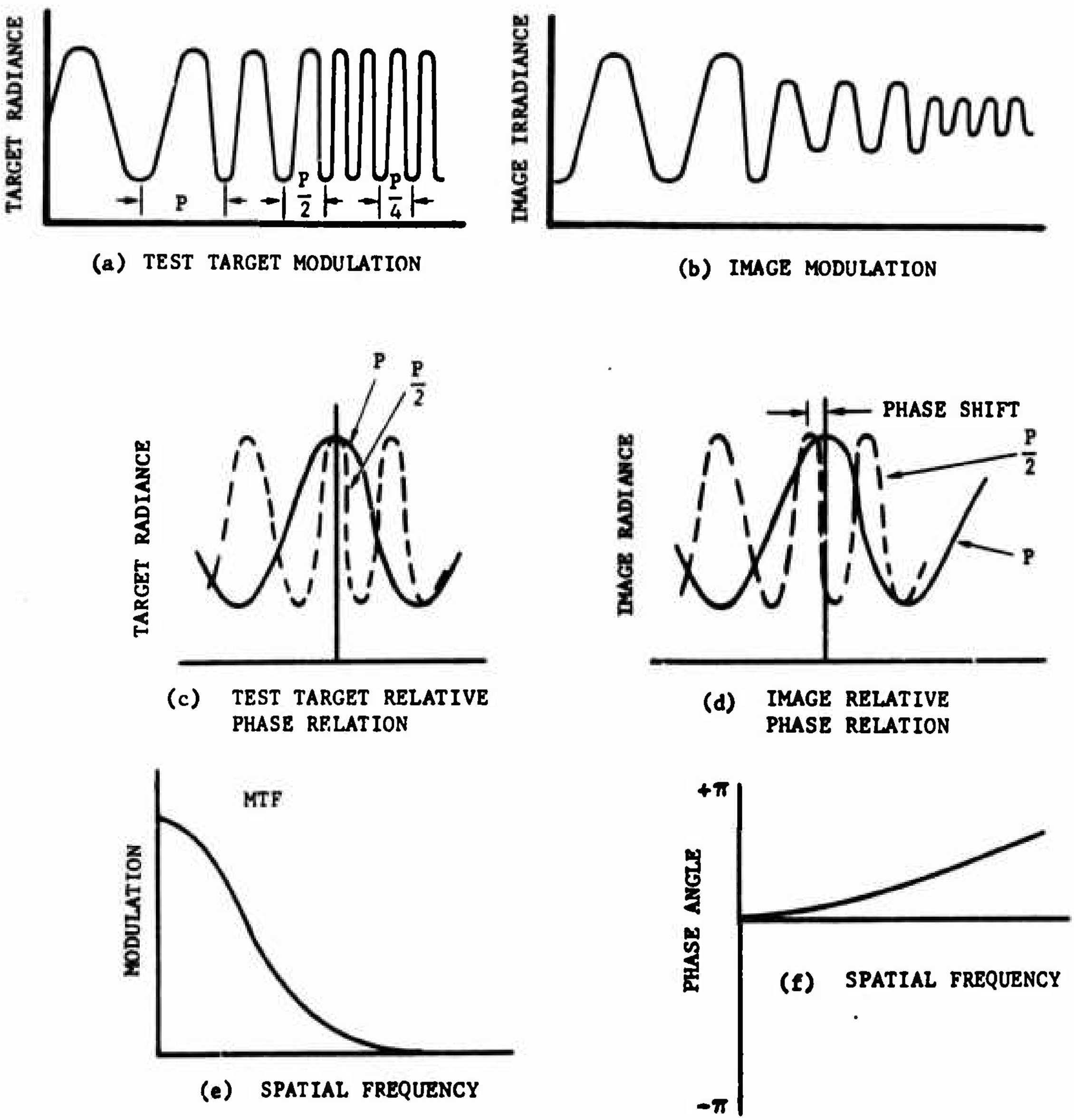


FIGURE 3.3-9. CONCEPTS OF SPATIAL MODULATION TRANSFER AND PHASE SHIFT

quite commonly measured and evaluated using Fourier transform techniques. The OTF is the Fourier transform of the system L.S.F., or equivalently

$$\text{OTF} = \frac{\text{Fourier transform (to spatial frequency) of image intensity distribution}}{\text{Fourier transform of object intensity distribution}} \; *$$

The line spread function is the resultant intensity distribution in the image plane when the object is an "infinitely" thin line. Since the frequency spectrum of the thin line is flat and contains all frequencies, the Fourier transform of the image is the measure of the frequency transfer characteristic of the system. A function similar to the LSF is the point spread function which is the image intensity distribution resulting from imaging a geometric point. The OTF is defined for the LSF because its spatial intensity character is a function of one dimension only. For the OTF to be strictly defined, the system that it describes must possess the qualities of linearity and spatial invariance. The linearity property of the system means that when the amplitude of the input signal is changed, the output signal changes in proportion without the generation of harmonics in the signal. Spatial invariance refers to the property that the image plane spatial properties are not dependent upon position in the image plane. In practice these requirements are rarely strictly met over the full range of system performance, but may hold over a small range of input signal and/or image position. The OTF is often used when not strictly defined (as long as linearity and spatial invariance requirements are not grossly violated) because it is practical and it does provide useful information.

It is easier for the system engineer to work in the spatial frequency domain than in the space domain. Any modification to the object frequency spectrum by components is handled by multiplication of the individual component MTF's (with some exceptions where the phase shift cannot be ignored). To determine the final image in the space domain he performs the Fourier transform on the image frequency content. To work in the space domain the analyst must perform cumbersome convolution integrations at each component interface in the imaging system.

In general, the system MTF is equal to the product of the individual MTF's of the components. Poor design at the interfaces of subsystems can result in significant reduction from this ideal case. An example of poor practice

*When one is concerned with the radiant distribution in the image plane, he is working in the space domain. When he is concerned with the spatial frequency spectrum of an image, he is working in the spatial frequency domain. The Fourier transform is the mechanism by which the change in variable from spatial coordinates to frequency coordinates is made.

is the failure to properly interface the sensor faceplate with the image plane of the optics.

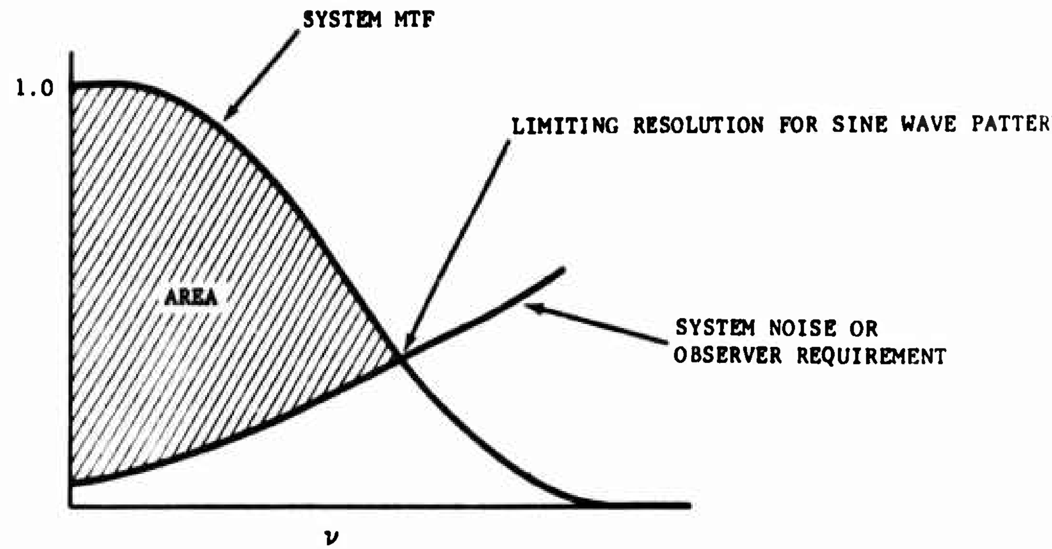
3.3.3.2.1 Common Test Methods

The OTF can be measured directly by using intensity modulated test targets of various spatial frequencies and observing the image formed by the system. Both the test target and its image are sinusoidally modulated. The modulation and phase of the image are referenced to the test target to determine the OTF. Another standard means to determine the OTF is to image a thin line through the system and measure the system line spread function. In practice the line width of the test target need be small compared to the highest spatial frequency of interest. The Fourier transform of the LSF is then performed, usually on a digital computer, and the OTF is thus determined. Matters of economics may sometimes determine the aforementioned methods to be impractical especially if it is known that phase shift is negligible. The square wave response (the response of the system to test targets consisting of bar charts of varying spatial frequency) is measured instead of the sine wave response. It is rather easy to make this measurement and the data can be converted analytically to the amplitude response of sine waves and then to MTF. Phase information is, however, not recoverable.

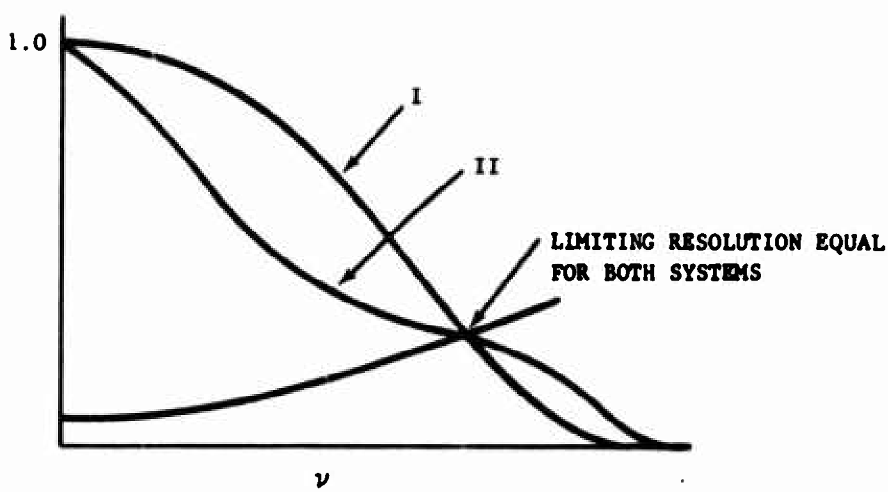
3.3.4 IMAGE QUALITY - (SEE ALSO PARAGRAPH 4.1.2)

Image quality, considering both information content and observer performance, is related in some manner to the MTF of the medium or system displaying the image. It is presently undecided what function best represents image quality. All functions presently being considered for the measure of image quality relate in some fashion to the area under the MTF curve and a threshold curve below which the transmitted image modulation cannot be detected. Figure 3.3-10(a) illustrates the principle. In Figure 3.3-10(b) both systems have the same limiting resolution. Since higher spatial frequencies represent edge construction in the actual image, both systems will have the same sharpness of high contrast contours but System II will present a considerably washed out image compared to System I because the modulation for System II at middle and lower frequencies is significantly degraded.

Limiting resolution can have very little to do with image quality as is demonstrated in Figures 3.3-11 and 3.3-12, where both images displayed have the same limiting resolution with obvious differences in image quality. In the bandwidth limited picture the ratio of modulation to required modulation threshold is significantly higher at lower and middle spatial frequencies than in the noise limited picture.

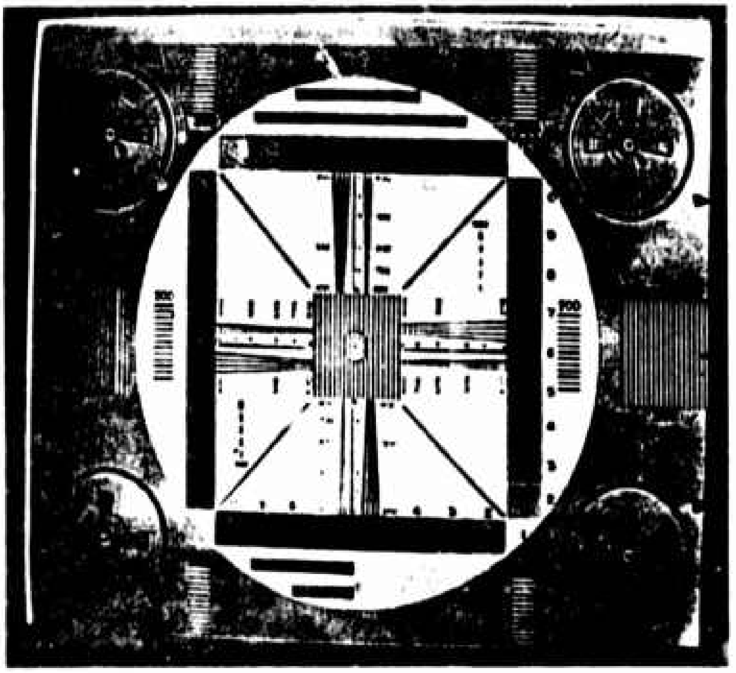


(a) AREA IS THE MEASURE OF THE IMAGE QUALITY



(b) COMPARISON OF TWO SYSTEM MTF'S

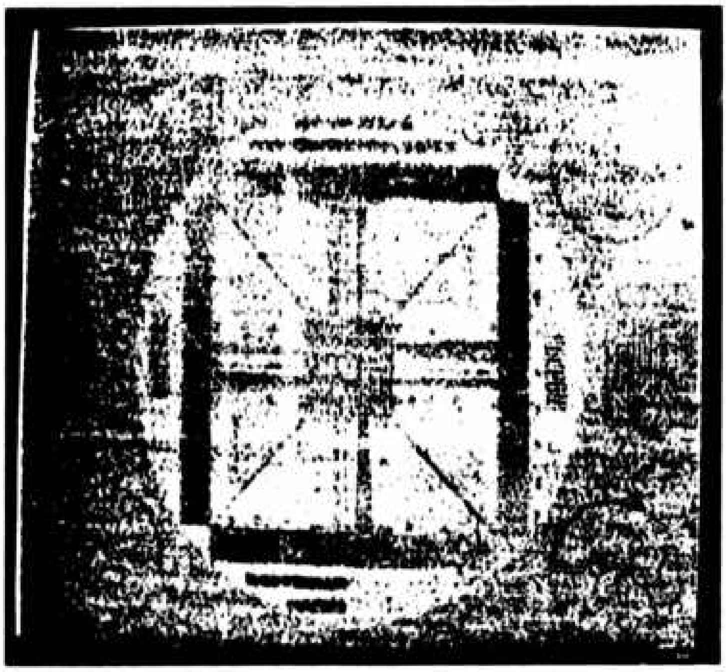
FIGURE 3.3-10 SPATIAL FREQUENCY CONTENT AS A MEASURE OF IMAGE QUALITY



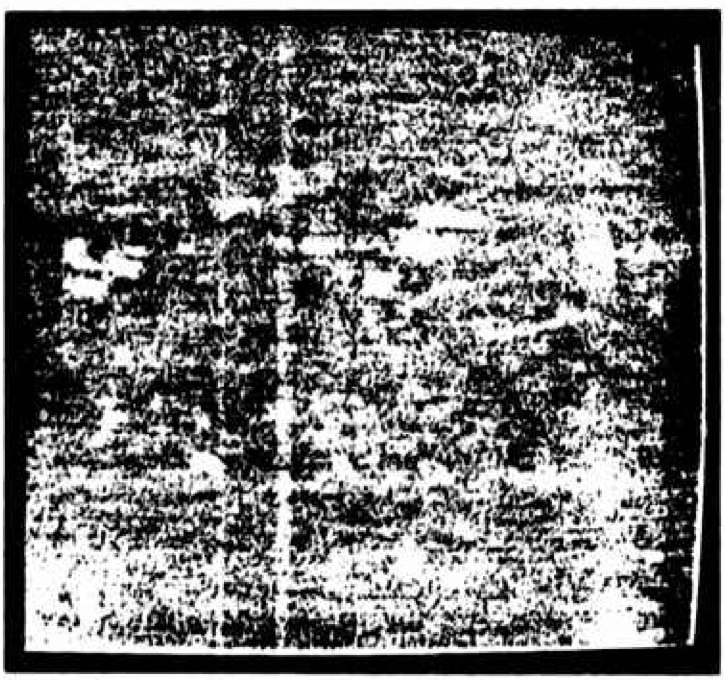
(a) RETMA CHART BANDWIDTH LIMITED TO 250 TVL

(b) SCENE BANDWIDTH LIMITED TO 250 TVL

FIGURE 3.3-11. PART A OF DEMONSTRATION THAT LIMITING RESOLUTION IS INADEQUATE DESCRIPTION FOR IMAGE QUALITY (11)



(c) RETMA CHART S/N LIMITED TO 250 TVL



(b) SCENE S/N LIMITED TO 250 VTL

FIGURE 3.3-12. PART B OF DEMONSTRATION THAT LIMITING RESOLUTION IS INADEQUATE DESCRIPTION FOR IMAGE QUALITY (11)

3.4 SIGNAL TO NOISE RATIO

Subsection 3.4 introduces the concept of the signal to noise ratio (which is a measure of the information content of the signal) as it exists in the electronic channel of this system and as it is displayed to the observer. It is important because the signal to noise ratio ultimately is the determinant of the quality of the displayed image. The general classes of noise are discussed and specific noise types which are important in electro-optical systems are delineated and discussed.

3.4.1 SIGNAL, NOISE AND THE SIGNAL TO NOISE RATIO (S/N)

Signal is the information flowing through the imaging system, including the observer, that corresponds to a radiance variation in the target scene. The signal will be variable as a function of time or position in the scene as the scene is scanned. The signal is radiant up to the point it becomes converted in the radiation transducer to an electrical voltage or current. At the display it is reconverted to a radiant signal for observer interpretation. Noise is any spurious or undesired disturbance which tends to mask the signal. It may occur in the radiant or the electrical information channel, as well as the display or observer. Noise will provide a lower limit for the useful dynamic range of the system. A measure of the information that is available in the signal channel is the amount by which the available signal exceeds the existing noise level of the system. This measure is usually expressed as a ratio called the signal to noise ratio. It is not uncommon for the units of signal to be different from that of the units used for the noise measurement. Often the noise is of a nature that the rms value of current or voltage is the most meaningful description while the signal character is best expressed by peak to peak values (as when one is interested in scene high lights and low lights) of voltage or current. The signal and noise may be expressed in other units and as a linear or logarithmic ratio.

Because the ultimate quality of the image will depend upon the S/N ratio, the important quantity to be determined as a function of scene radiance is the signal to noise ratio and not the transducer sensitivity. The limiting resolution of TV sensors is a function of the S/N ratio and where the noise level is fixed and independent of the input radiation level, the limiting resolution is usually expressed in terms of scene radiance (Paragraphs 4.5.3.1, 4.7.2). Unless the character of the noise is such that it can be selectively filtered, the input S/N ratio cannot be improved as the signal flows through the system. The design emphasis is then to minimize the number and magnitude of additional noise sources within the system.

3.4.2 VISUAL SIGNAL TO NOISE RATIO (See also Paragraph 4.1.2)

The S/N ratio can be determined anywhere in the information channel with the most common places being in the electronic video channel and at the display surface. The S/N ratio to the observer looking at the display will be significantly improved from that measured in the electronic channel. He is able to achieve this improvement because his eye will integrate both the signal and the noise over space (2 dimensions) and time. As the noise has a random component and the signal (displayed scene) has a coherent structure, the integral S/N as experienced will have been substantially enhanced from that of the video channel. If the noise is structured or fixed pattern (Paragraph 3.4.3) the integration performed by the eye equally enhances signal and noise, and the S/N ratio is not improved as in the manner when the noise is random. The display noise is witnessed by the observer as the display luminance fluctuations associated with viewing a target against the background. It is the ratio of the signal (the luminance difference between the target and its background) to these fluctuations that is the visual S/N ratio or the display S/N ratio. Experiment has shown the detection probability for simple targets is related to S/N ratio at the display (Paragraph 4.1.2.4). The concept can be extended to define the threshold detection requirements for the observer in the presence of a noisy image.

3.4.3 NOISE

Noise may be random, in which case it is statistically describable, or it may be of the fixed pattern type. Random noise is inherent in both the arrival rate of photons from the scene, from the scanning process in pickup tubes, and from the amplifying process of video electronics. Depending upon sensor type, amount of intensification (for pickup tubes), and electronics design, one of the random noise sources will generally provide the lower limit to system performance. Fixed pattern noise such as hum or noise patterns due to improper scanning rates should be sufficiently under control in a well designed and manufactured system that they are not the system performance limit.

Noise may be additive noise or a product noise. An additive noise is one that adds to the signal, usually according to the laws of statistics. It is present even when no signal is present. A product noise is one that results from the transmission of the signal through the system and is significantly reduced when the signal is removed. Typical of this second type is photoelectron shot noise and phosphor grain noise. The signal to noise ratio for product noise is proportional to the square root of the signal.

The effects of noise are usually evaluated in terms of frequency content. The noise frequency spectrum is modified by MTF (or electronic bandwidths) and is additive on an RSS (Root Sum Square) basis at each frequency if the noise sources are independent and random. The system engineer should be

concerned with the effect the system noise will have on observer performance and what magnitude of noise is permissible for the assigned observer task. Complete definition of the relationship of observer field performance to the amount of displayed noise is not yet possible. However, boundaries, which provide a basis for estimating the minimum acceptable S/N ratio, have been established for displayed scenes of simple targets on simple backgrounds (see Paragraphs 4.1.1.5 and 4.1.2.4).

3.4.3.1 Noise Types

a. Photon Noise. Light quanta arriving from the scene will arrive with statistical fluctuations in their numbers. If the number of quanta is sufficiently small and other noise sources are well under control, photon noise will provide the ultimate noise limit.

b. Johnson (Nyquist) Noise. Thermal fluctuations of electrons in resistors is responsible for Johnson noise. Generally the input impedance to the video preamp provides the prime contribution to this noise as it is possible that at this point there has been insufficient video gain to overcome the resistance noise contribution.

c. Shot Noise. In a manner similar to photons arriving at a surface, the number of electrons leaving or arriving at a surface (such as a photocathode) in a unit of time will also fluctuate statistically. The scanning beam of a TV pickup tube will in some types of tubes provide the limiting system noise.

d. 1/f Noise. Currents across junctions and contacts in detectors generate a random noise known as 1/f noise due to the characteristic of the frequency spectrum of the noise.

e. Fixed Pattern Noises. Phosphor and photocathode grain patterns are usually insignificant. Dead or weak detectors will cause holes in the raster of FLIR displays corresponding to the location of the dead detector in the scanning array (Paragraph 4.5). Pick-up such as hum is possible if care is not taken in both the design of the imaging system and its integration with other systems. If the sampling rate is not high enough compared to the information frequencies to be sampled, beat frequencies (side bands) called aliases will appear within the signal bandwidth and will generate visible patterns on the display (Paragraph 4.7.3).

SECTION 4

SYSTEM COMPONENTS

This section begins with the consideration of what is necessary to couple information from the displayed scene to the observer. Even though some of the observer requirements for real-time imaging in an adverse environment are still poorly defined, any system design that does not consider the observer or considers him to be in laboratory environment is probably well on the way to establishing a poor field performance record. It is then logical in performing the system analysis to start with the observer requirements and the physical set of conditions describing the target scene. With the exception of some operational freedom, the system designer is constrained by the observer on one end and the scene characteristic on the other. This section is developed in that sense with system components and performance analysis following the definition of the operating boundaries imposed by the observer and the scene.

4.1 THE EYE AND THE OBSERVER

The essence of the real-time imaging problem is to give the observer a displayed image that is adequate for him to perform his job. The image must possess certain qualities to be useful. These qualities are defined in terms of observer requirements and includes such variables as displayed image size, display brightness, crispness or fidelity in the image, and displayed noise levels. Much of the available data relating to observer requirements is from laboratory measurements and must be adjusted before it is applicable to describing general observer requirements (Subsection 4.1).

addresses the matter of observer requirements in two steps. The first step is Paragraph 4.1.1 and considers visual performance as limited by human physiology. Paragraph 4.1.1 includes spectral response, spatial discrimination abilities, contrast thresholds, and temporal properties of human vision. Step two, Paragraph 4.1.2, is concerned with the practical matters of displaying the image to the observer. Paragraph 4.1.2 integrates the observer performance limits from Paragraph 4.1.1 with other pertinent data to determine the requirements for the displayed image. Included are considerations of display size; image motion; briefing effects; observer detection and recognition requirements including contrast, target size, and system resolution; displayed noise; and image quality.

4.1.1 PHYSICAL PERFORMANCE FACTORS OF THE HUMAN EYE

4.1.1.1 Spectral Response

There are two types of sensors, cones and rods, in the eye which convert input radiation to neural responses for use by the brain in perceiving the observed image. Which of the sensors is dominant depends upon the level of ambient illumination to which the eye is adapted. When the eye is light adapted, the cone mechanism is dominant. Cones are concentrated in an area of the retina called the fovea and form the central vision which is most sensitive to fine spatial discrimination. The area of the retina which is most sensitive to spatial detail extends approximately ±10 degrees in azimuth and ±7.5 degrees in elevation from the fovea. The spectral characteristic of the light adapted eye is called the photopic eye curve; and for photometric purposes, the photometric eye curve has been standardized to that in Figure 4.1-1.

During dark adaptation of the eye, the rods become dominant and precipitate a shift in the spectral response function of the eye to the scotopic eye function. The eye pupil size will change from approximately 2mm in diameter to 8mm. It takes approximately 30 minutes for the eye to become dark adapted and during that time the eyes' sensitivity to ambient illumination increases by over a factor of 1000. Scotopic vision, however, is peripheral; and spatial sensitivity is significantly worse than with the photopic eye. (See Figure 4.1-3 for relation of minimum detectable target size versus light level.) When dealing with a real-time imaging system where observer performance is to be maximized, only the photopic eye data apply. In fact under most conditions, dark adaptation and good display coupling to the observer are mutually exclusive. After having been conditioned to the dark adapted state, it will take an observer from 1 to 3 minutes to achieve a light adapted state for display viewing.

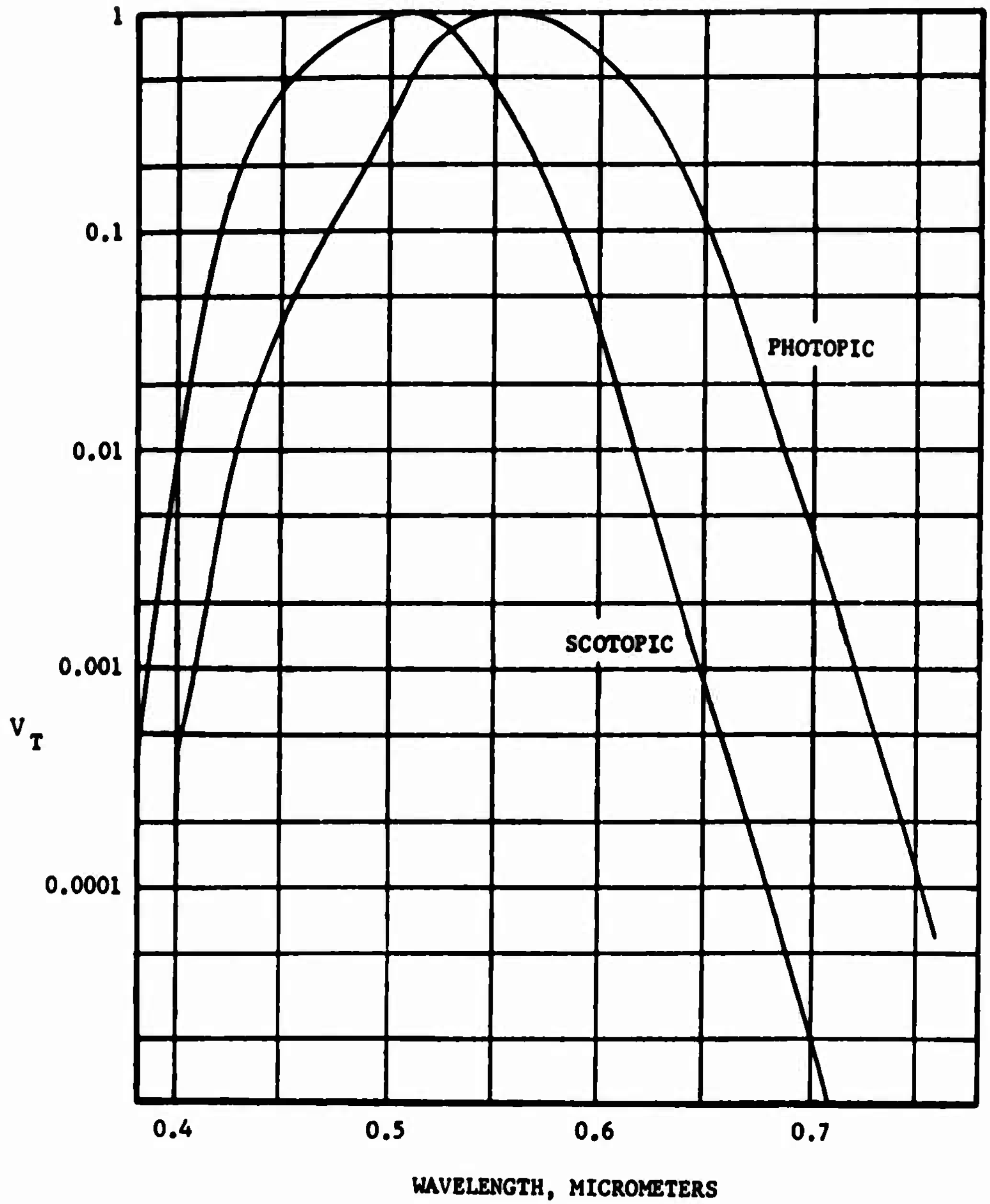


FIGURE 4.1-1. THE RELATIVE LUMINOUS EFFICIENCY OF RADIATION (27)

4.1.1.2 Resolution and Spatial Discrimination

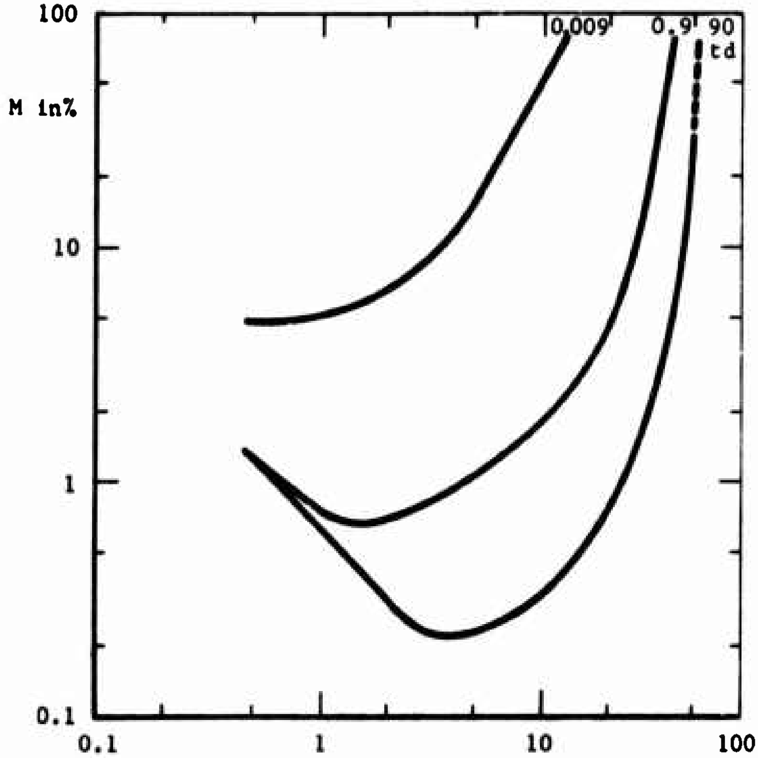
The resolution threshold of the human eye in discerning the separation of adjacent points under optimum viewing conditions is about 1 minute of arc or 0.29 milliradians (one degree equals 17.5 milliradians). This is an absolute threshold, however, and a value of 1 milliradian is usually taken to be the comfortable resolution ability of the eye for point targets against a uniform background (125).

As was discussed in Section 3.3, the perceived display quality is a function of the area between the system MTF curve and the observer detection requirement at each spatial frequency. To assign a value to this area, it is necessary to know in some respect what the observer needs in terms of modulation as a function of spatial frequency. Threshold modulation values for sine wave intensity modulated images have been determined as a function of spatial frequency by Van Nes and Bouman (71) and others. Figure 4.1-2 is taken from this reference. The data are plotted in units of retinal illuminance called trolands. If the pupil area is known, this value can be equated to a target radiance, and for a 2mm diameter pupil the conversion from trolands at the retina to footlamberts at the test object is footlamberts = trolands + 10.8. The plotted values are representative eye performance for red, green and blue illumination. Note the increased sensitivity to modulation detection as illumination is increased. The lower curve (90 trolands) is approaching the limit of improved sensitivity as a function of retinal illuminance. The lower curve is consistent with values of display luminance currently available (Section 4.2). The shape of the curve is also significant. It says that the frequency spectrum of a displayed target will be modified in such a manner as to enhance the middle frequencies while attenuating lower frequencies. This has implications as to how the displayed contrast of the target will be perceived. If the target is sufficiently large only the contrast difference around the perimeter of the target will be significant in defining the target contrast (70).

4.1.1.3 Contrast Performance

4.1.1.3.1 Thresholds

The contrast threshold is that point at which the human observer is able to detect, at some specified probability level, the target image within its background due to differences in the apparent luminance between the target and the background. An introduction to the concept of contrast is found in Section 3.2. The contrast threshold is a function of the displayed luminance, size and shape of the target, boundary sharpness, scene distractions (clutter) and observer requirements. (The observer requirements are sometimes ill defined but they nonetheless do exist and are some of the variables in determining the threshold level.)



SPATIAL FREQUENCY IN CYCLES PER DEGREE

(SEE PARAGRAPH 4.1.1.2 FOR DISCUSSION OF TROLAND)

FIGURE 4.1-2. THRESHOLD MODULATION CURVES FOR λ = 525 NANOMETERS AT THREE ILLUMINANCE LEVELS (71)

Blackwell (73) has established the contrast threshold for the human eye for circular targets against a uniform background. (This data is sometimes called the "Tiffany" data.) The contrast threshold as a function of target size and ambient adaptation level is presented in Figure 4.1-3. Note that this data is for a 50 percent probability of detection and at this level the observer was not confident that he had seen the target. Blackwell notes that the observers under test did not feel that they had "seen" the target unless the level of probability of detection was 90 percent. The Blackwell data can be adjusted for other probabilities of detection by use of Figure 4.1-4. It is only necessary to multiply the contrast value for 50 percent (Relative Contrast = 1) from Figure 4.1-3 by the relative contrast figure defining the described probability level. The contrast level for 90 percent, the point at which the target was "seen" is therefore 1.62 times the levels of Figure 4.1-3. Note that only a certain range of the data really applies to the real-time imaging problem; this is the region defined by acceptable display luminances. The luminance range which is nominally "acceptable" is from 1 to 100 footlamberts but may well go over 1000 footlamberts if the display is located where the ambient light level is quite high (See Section 4.2). Blackwell also investigated the detection of negative as well as positive contrast. Positive contrast implies that the target radiance, L_{TARGET}, is higher than its background radiance, $L_{BACKGROUND}$, and is defined by

$$C = \frac{L_{TARGET} - L_{BACKGROUND}}{L_{BACKGROUND}}$$

and ranges from $C = 0$ to $+\infty$.

Negative contrast implies the target is less bright than the background and is defined by

$$-C = \frac{L_{BACKGROUND} - L_{TARGET}}{L_{BACKGROUND}}$$

and ranges from $-C = 0$ to 1.

For the range from $+C = 0$ to 1 and $-C = 0$ to 1 for luminances and target size consistent with satisfactory observer performances, the Blackwell data are equally applicable to positive and negative contrasts. (For additional discussion on the subject of contrast see Paragraph 4.3.3.)

Hanes and Williams (1948) have pointed out the observer's differential brightness sensitivity is maximized when his eyes are adapted to a luminance level close to that of the display in use. This has significant meaning for the viewing distance of the observer, or equivalently the

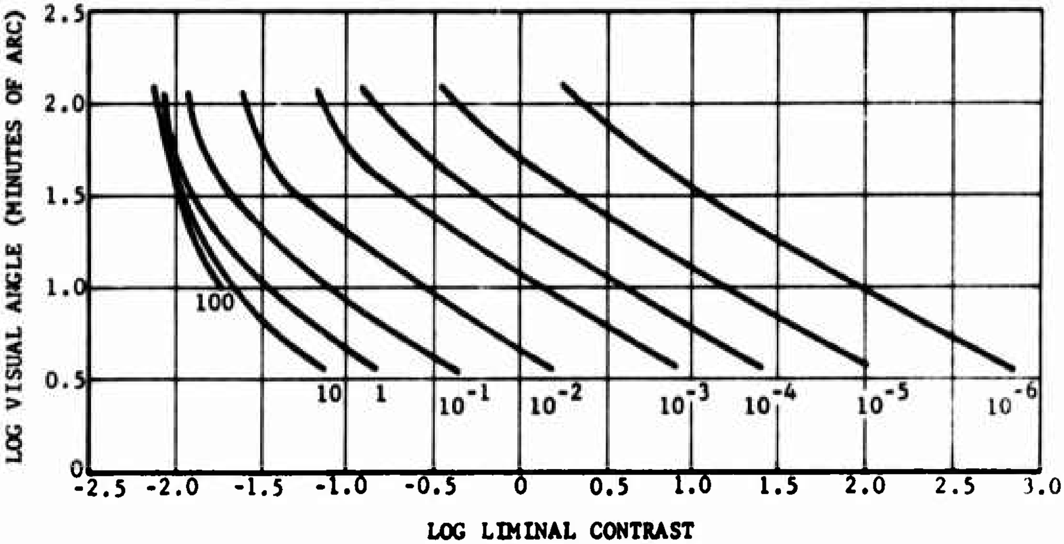


FIGURE 4.1-3. RELATION BETWEEN THRESHOLD CONTRAST AND STIMULUS AREA FOR A GIVEN ADAPTATION BRIGHTNESS. BRIGHTNESS VALUES IN FOOTLAMBERTS (73)

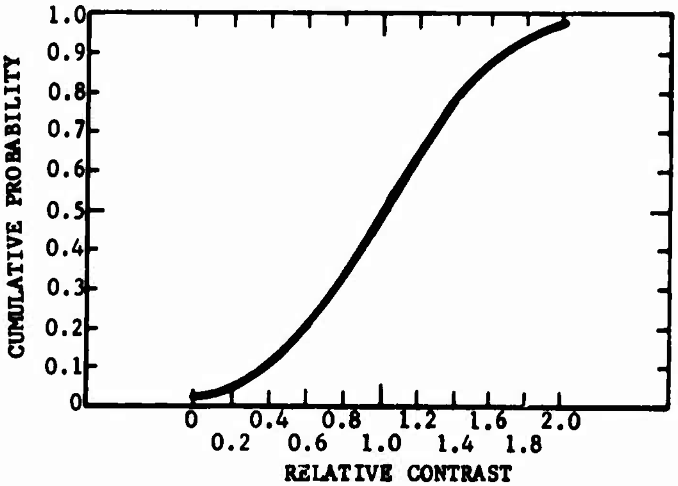


FIGURE 4.1-4. AVERAGE PROBABILITY CURVE (73)

solid angle the display subtends, and the background against which the display is located.

In Figure 4.1-5 the data of Van Nes and Bouman (71) discussed in Paragraph 4.1.1.2 is presented in a different manner. In gathering this data it was required that the observer be certain that the sine wave intensity pattern was present. This data is therefore approximately representative of the 90 percent level of detection.

Contrast thresholds in a scene that contains a nonuniform and cluttered background and irregular targets are more difficult to determine (being a function of the highly variable scene content), but when the targets are of sufficient size and their borders are sufficiently well defined against the background, the contrast thresholds at the border apparently agree with contrast thresholds determined against a uniform background (70).

4.1.1.4 Temporal Properties

4.1.1.4.1 Critical Fusion Frequency

The flickering appearance of a modulated light source disappears when the frequency of intensity modulation becomes sufficiently high. The lowest frequency at which this occurs is called the critical fusion frequency (CFF).

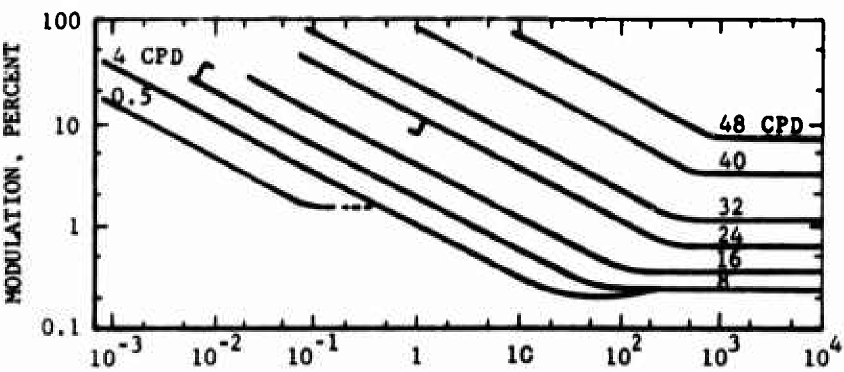


FIGURE 4.1-5. THE DEPENDENCE OF THRESHOLD MODULATION ON RETINAL ILLUMINANCE FOR EIGHT SPATIAL FREQUENCIES (IN CYCLES/DEGREE) AND GREEN LIGHT, λ = 525 NANOMETERS PUPIL DIAMETER EQUAL TO 2 MM (71)

It must be considered in a real-time imaging system where the information will be displayed as serial frames of information. Framing will produce a display luminance that is modulated in time, and unless the frame (field) rate is sufficiently high, the flickering display will be a source of noise and irritation to the observer.

At normal display luminances, CFF is not a function of wavelength (Figure 4.1.6). It is a strong function of average display luminance. Figures 4.1-7 and 4.1-8 present the data from Kelly (1961) in two different manners for eye sensitivity to sinusoidally modulated intensity fields. The second scale of the figures converts the retinal illumination to target luminance assuming a 2mm diameter pupil. The eye has a braod peak response to intensity modulation ranging from 5 to 50 hertz. The plotted data demonstrates the difference in the perception of modulation at low and high temporal frequencies. At higher frequencies according to Figure 4.1-7, only the modulation amplitude, not the percentage modulation, is important. This means any flicker of sufficient amplitude will be observed regardless of the display luminance. At lower frequencies (Figure 4.1-8) only the modulation percentage is important and flicker can be eliminated by adding a dc level of luminance.

Figure 4.1-9 illustrates how the data of Figure 4.1-8 is used to determine the CFF as a function of modulation percentage. Note that at 100 percent modulation the CFF is 40 hertz and increases with retinal illuminance. A plot of the intercept of the 0.01 relative sensitivity level with the individual curves would represent the CFF as a function of retinal illuminance for 100 percent modulation.

Square wave modulation would give slightly different results than sinusoidal modulation, but for the higher frequencies in which one is interested for imaging systems, the higher harmonics are not sensed by the eye. Because only the fundamental of the square wave is then important, the sinusoidal data can be adjusted by a constant for the difference in modulation between a period sine wave and the amplitude of the fundamental of a periodic square wave.

Figure 4.1-10 shows the interaction effect with edges of the scanning eye in sensing a flickering field. Shape of displayed field is important at lower temporal frequencies in sensing flicker but not important at framing rates common to imaging systems.

4.1.1.4.2 Eye Integration Time (Storage Time)

The eye/brain combination does not process image information instantaneously. Through memory and through physiological changes on the retina resulting in a physical collection of the radiant image, the eye/brain combination accumulates image information for a period called the eye integration or

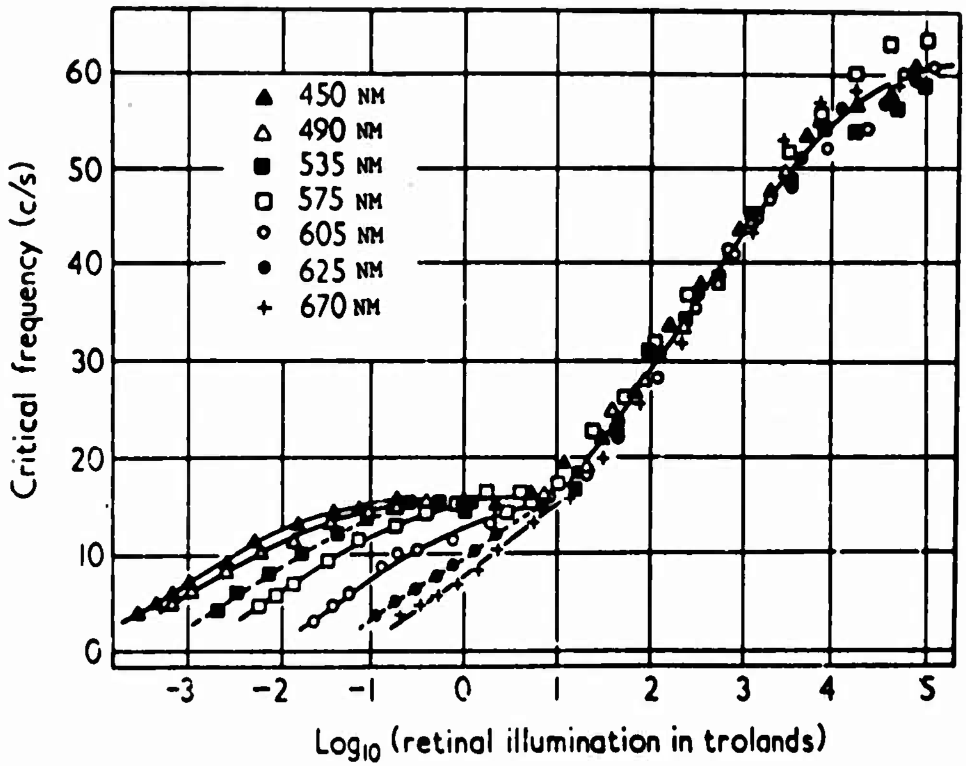


FIGURE 4.1-6. CRITICAL FUSION FREQUENCY AS FUNCTION OF WAVELENGTH (NANOMETERS) AND RETINAL ILLUMINATION (28)

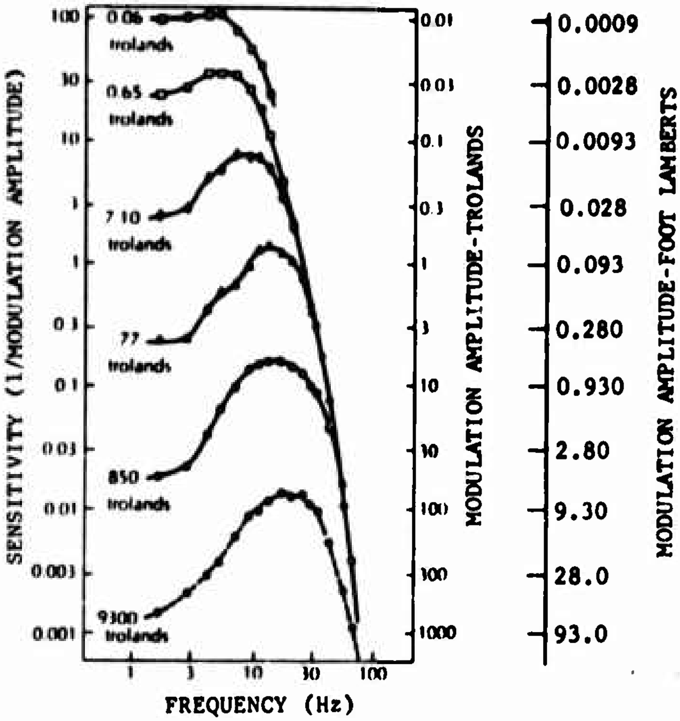
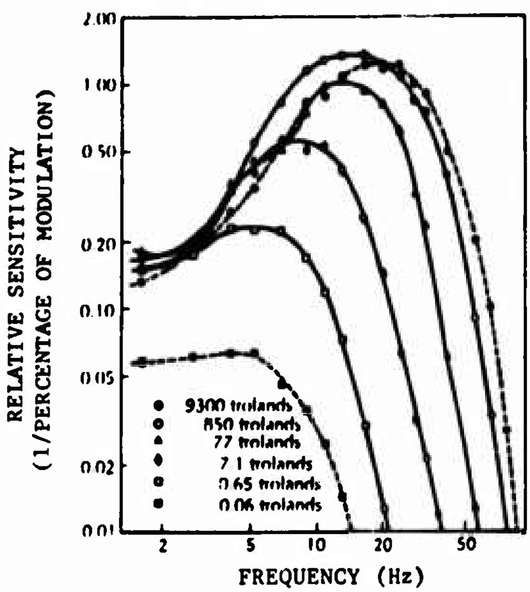


FIGURE 4.1-7. SENSITIVITY OF THE EYE TO TEMPORAL SINUSOIDAL MODULATION OF INTENSITY (6)



CONVERSION TROLANDS TO FOOT LAMBERTS (2 MM EYE)

TROLANDS		FOOT LAMBERTS
9300	-	860
850	-	79
77	-	7.1
7.1	-	0.66
0.65	-	0.06
0.06	-	0.055

FIGURE 4.1-8. RELATIVE SENSITIVITY OF THE EYE TO TEMPORAL SINUSOIDAL MODULATION OF INTENSITY (6)

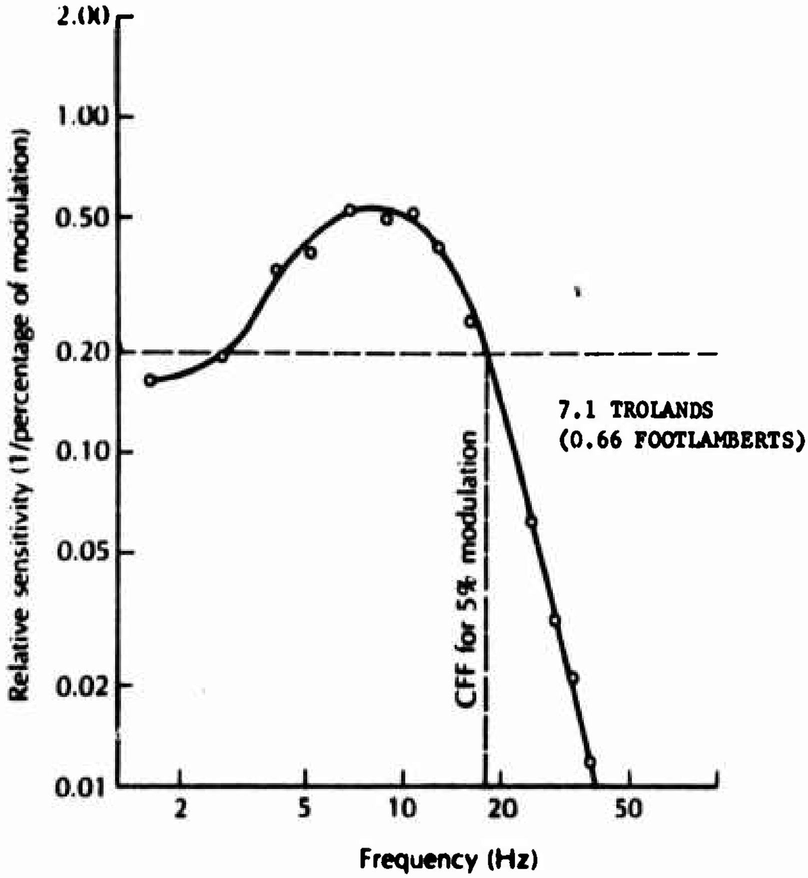


FIGURE 4.1-9. CRITICAL FUSION FREQUENCY AS A FUNCTION OF MODULATION PERCENTAGE (6)

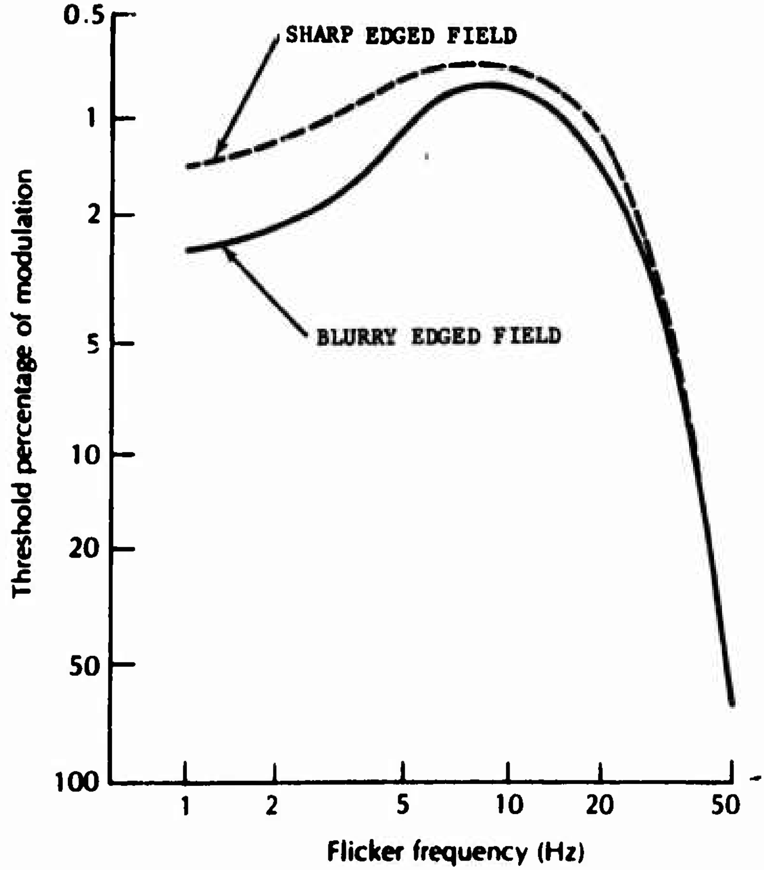


FIGURE 4.1-10. TEMPORAL MODULATION TRANSFER FUNCTIONS FOR SMALL FLICKERING FIELDS AGAINST A NONFLICKERING BACKGROUND

storage time. It is the collection of light quanta over this period that is perceived as the image. According to Rose (3) who considered his own work and that of others, the value for eye storage time for normal display luminances (1 to 100 footlamberts) is between 0.18 and 0.25 second. The value most often used is 0.2 second. At threshold light levels the value for storage time is more in doubt and may be as long as 1 second (73).

4.1.1.5 <u>Applicability of Eye Performance and Threshold Data to Defining the Display/Observer Interface</u>

In some instances visual performance measures are directly applicable to defining the requirements for the design of an imaging display. In other instances the field viewing conditions are significantly worse than the ideal laboratory conditions in which the performance data were obtained. In these cases significant adjustments must be made in the data to bring it close enough to defining the observer requirements in the anticipated environment such that a useful imaging system design can be defined. Examples of directly applicable data are the critical fusion frequency and display luminance requirements for good visual performance. Other factors in the problem may require upgrading these requirements, e.g., a high background brightness will force a display luminance to be brighter than is normally necessary.

It is optimistic folly to believe that threshold contrast and resolution data describe the minimum observer requirements for field conditions. While the resolution of the eye is 0.29 milliradian to 1.0 milliradian, it has been demonstrated the minimum target size for good detection performance against a simple background by an observer is 12 to 20 minutes of arc (4 to 7 milliradians) (52) for normal viewing distances. The target may even have to be larger if the scene is cluttered.

After the observer has detected the target, his resolving power (1 milliradian) may be used to discriminate detail in the target. A system design, which considers only the resolving power of the observer and not the required minimum detection size, will have insufficient magnification by the ratio of the minimum detection size to the observer resolving power, a factor from 4 to 7 power, to do the job.

Laboratory contrast thresholds are similarly inadequate levels about which to design an imaging system. The exact threshold requirements for a given scene and environment are in practice impossible to obtain but reasonable contrast levels are defined by systematically upgrading the laboratory threshold values (see Paragraphs 4.7.2.3 and 4.7.2.5). Baily (69) has done this for some of the Blackwell data and his results for an average display brightness of approximately 60 foot/lamberts for 50 percent detection are plotted in Figure 4.1-11. The scale factor used by Baily is 5.5 times the laboratory threshold. This same logic would apply to

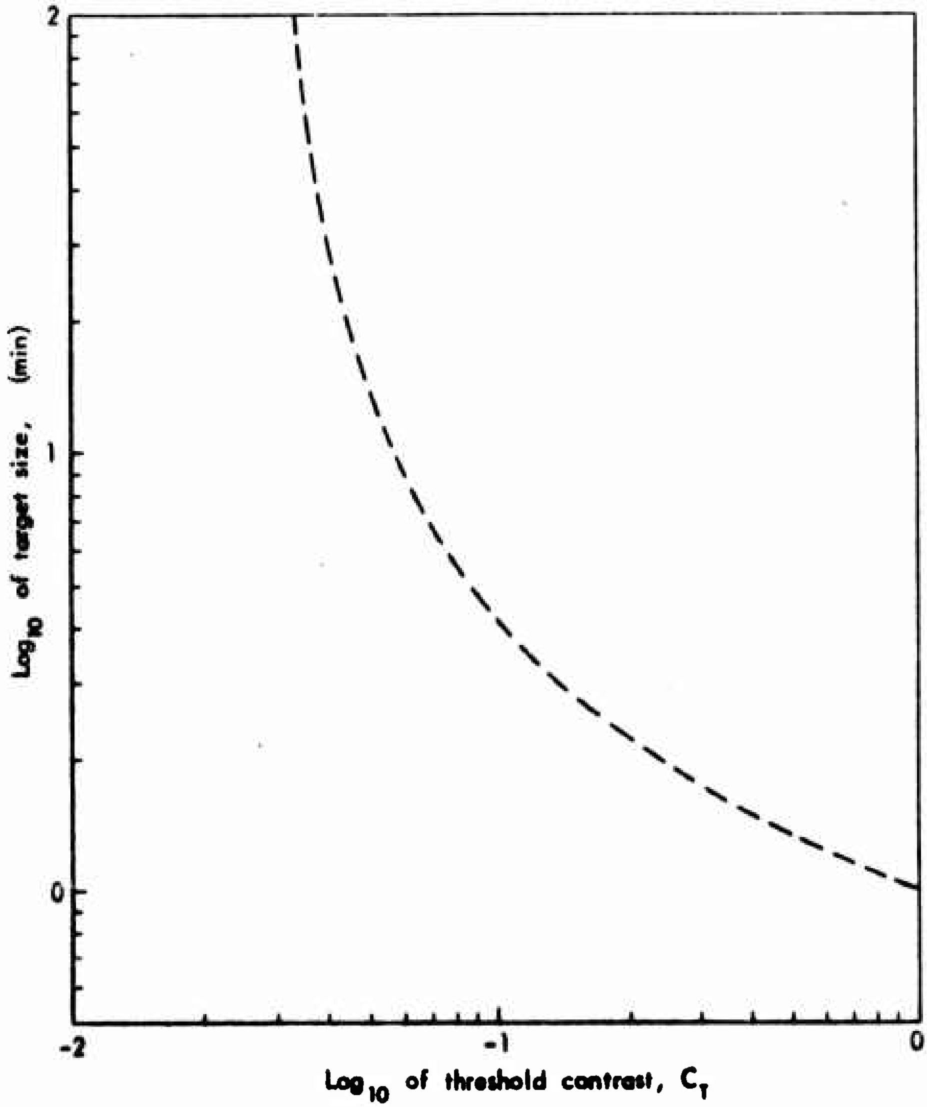


FIGURE 4.1-11. THRESHOLD PERFORMANCE OF THE EYE. BRIGHTNESS APPROXIMATELY 60 FOOTLAMBERTS.

In addition to diffraction effects, the aberrations of an optical system distort the incident wavefront. In most cases it is aberration rather then diffraction that determines the limiting capability of the optical system.

When aberration is small and both aberration and diffraction determine imaging performance, the wavefront distortion due to aberration or misfocus is measured in a unit called a Rayleigh limit. The value of a Rayleigh limit is a $\lambda/4$ path length difference between the actual wave and the "perfectly" converging wavefront converging upon the paraxial focus (see Figure 4.4-13 and Smith).

The effect of diffraction and small amounts of aberration upon system MTF* (3.3) have been published (85, 84) and are reproduced in Figures 4.4-14 and 4.4-15. Figure 4.4-16 shows the effects of circular obscurations, as in a Cassegrain optical system, upon system MTF (see Section 3.3). The units of the abscissa are normalized spatial frequency relative to the cutoff frequency of the optical system. The cutoff frequency is that spatial frequency (see Section 3.3) at which diffraction effects reduce the modulation that was present at the system input to zero modulation in the image. The cutoff frequency ν_o is

$$\nu_o = \frac{1}{\lambda(f/\text{number})}$$

and ν_o is in cycles per millimeter if λ is in millimeters.

4.4.4 TYPES OF OPTICAL SYSTEMS AND COMPARATIVE ADVANTAGES

The basic types of imaging optics are refractive which consists of lenses, reflective which consists of mirrors, and catadioptric which consists of both refractive and reflective elements. Well known designs of any of the systems may be referred to by name such as Cassegrain, which is a reflective system, or Schmidt which is a catadioptric system.

4.4.4.1 Refractive Systems

Chromatic aberration is the most significant limitation to refractive systems for use with wide spectral bands. With some difficulty and sacrifice in angular coverage, it is possible to cover a 2:1 range of spectral values (as an example, 0.5 micrometers to 1 micrometer). In practice it is difficult to achieve an f/ smaller than 0.9; but for large fields (>40° total field) with good chromatic aberration and reasonable cost, f/ equal 1.5 represents a reasonable limit. A refractive system is illustrated in Figure 4.4-17.

*MTF is a measure of the systems ability to reproduce fine scene detail in the image.

Recognition and identification are primarily dependent upon the resolution (image detail) in the displayed target area.

There is already a considerable amount of data (see remainder of Paragraph 4.1.2) relating to observer performance as a function of display parameters (display size, number of scan lines, etc.). Some of the data is contradictory and much has limited applicability. Some of the key parameters can be discussed as they affect observer performance, but as most of the parameters interact in complex fashions, definitive design guides cannot be given. The more common measures of observer performance are his probability of detection (or recognition or identification), search time, and number of observer judgement errors.

4.1.2.1 Detection

4.1.2.1.1 Contrast, Image Size and Resolution

The general relationship between contrast, size and visibility in a non-search situation is shown in Figures 4.1-12 and 4.1-13 (32). A relationship of this type, plus an additional requirement that the minimum size for threshold detection is met, is one traditional manner used to determine the point at which detection will probably occur. One value in general usage for minimum detectable target size (from the work of Steedman and Baker, Figure 4.1-14, and Ludvig and Miller, Figure 4.1-15) is 12 to 20 minutes of arc (52), (53). Their values are for abstract targets against a uniform background; and depending upon actual operational conditions, may be optimistic. Two additional display/observer coupling parameters should be also considered. The smaller, higher contract figures of Figure 4.1-13 would not be equally detectable in a dynamic viewing condition as display motion relative to the observer will degrade the smaller images to a greater extent than the large ones. (See Section 4.6 for treatment of sight-line motion in MTF degradation.) This effect may be appropriately included in the minimum threshold size. Work by Swinney et al (70) indicates that the actual minimum target size required for detection is a function of display size, as the ratio of target image area to display area bears a closer relation to probability of detection than does absolute image size. Figure 4.1-16 shows detection performance for a fixed viewing distance of 24 inches for a 3, 6 and 9-inch display.

At a fixed image size of 30 minutes of arc, the probability of detection is not constant for all three display sizes. The fixed image size results in a larger portion of the smaller display area being occupied by the target. The probability of detection for the 30 minute image is 53 percent for the 3-inch display, 45 percent for the 6-inch display and 25 percent for the 9-inch display. Note in Figure 4.1-16 that the 6 and 9-inch displays demonstrate a break in performance at approximately the size demonstrated by Steedman and Baker (52).

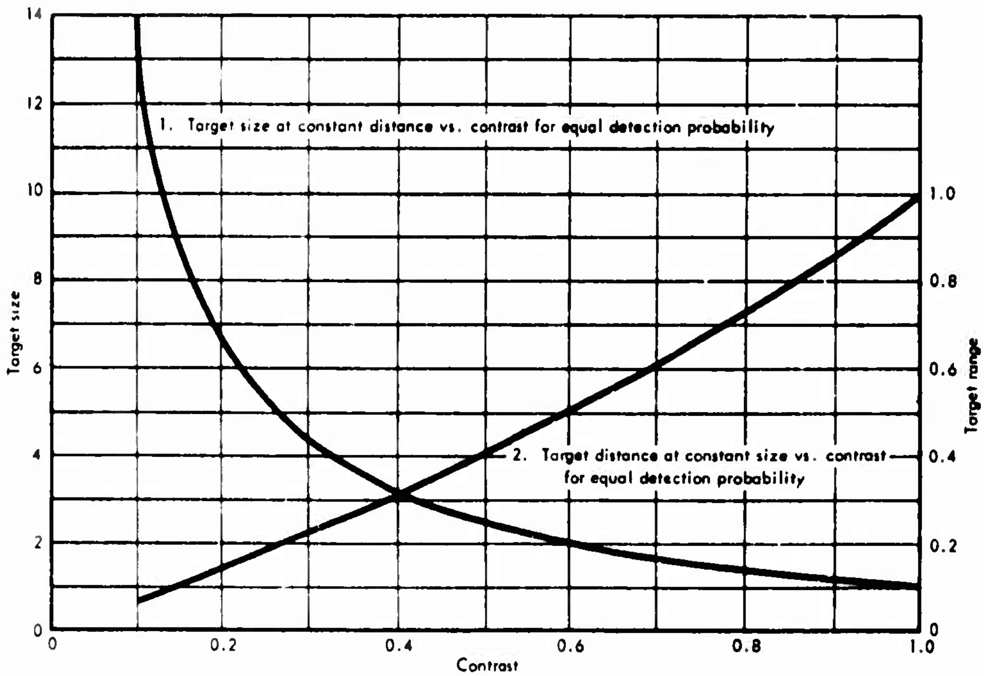


FIGURE 4.1-12. SIZE CONTRAST AND RANGE RELATIONSHIP (32)

FIGURE 4.1-13. SIZE VERSUS CONTRAST TO YIELD CONSTANT READABILITY (32)

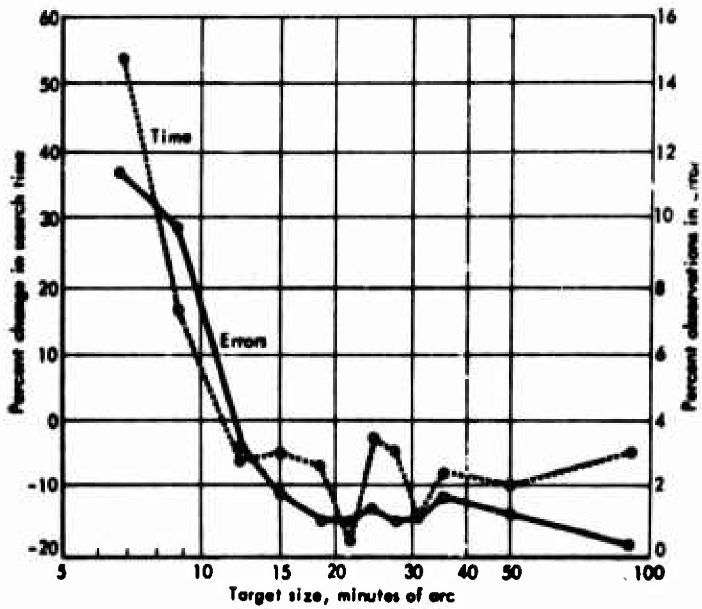


FIGURE 4.1-14. RELATIVE INCREASE OR DECREASE IN MEDIAN SEARCH TIME AND FREQUENCY OF ERRORS AS A FUNCTION OF THE VISUAL ANGLE SUBTENSE OF THE TARGET (52)

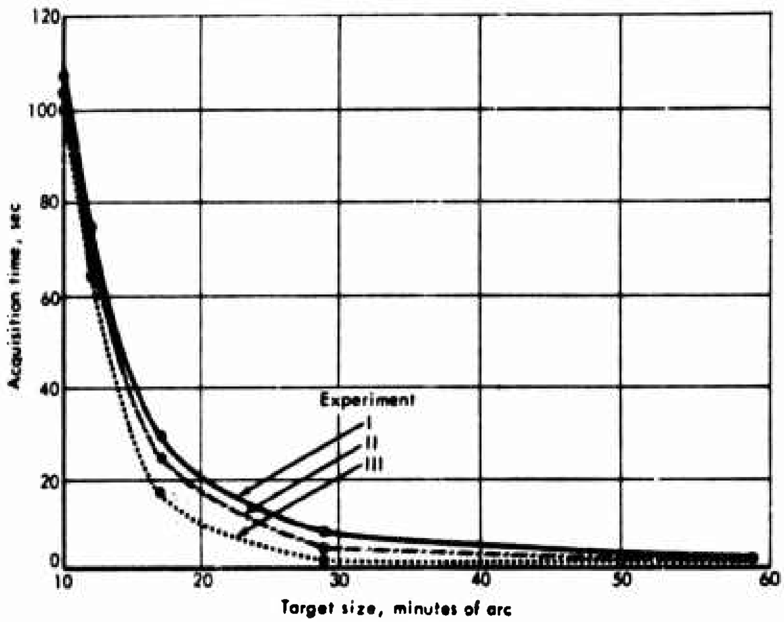


FIGURE 4.1-15. MEAN ACQUISITION TIME OF THREE SUBJECTS (53)

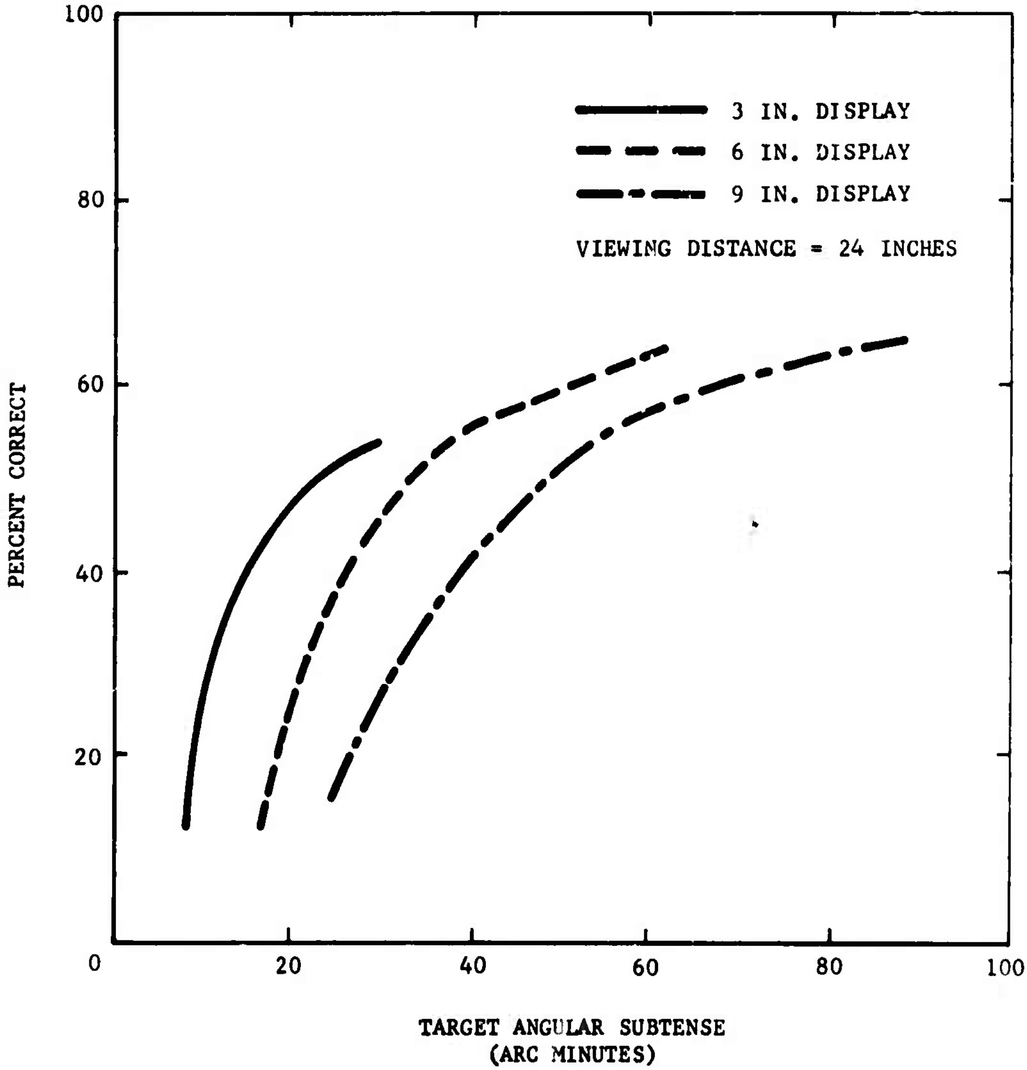


FIGURE 4.1-16. DETECTION PROBABILITY AS A FUNCTION OF THE ANGULAR SUBTENSE OF TARGETS FOR THREE DISPLAY SIZES (70)

In Figure 4.1-17 additional Swinney data is presented to demonstrate the interactions of display size, target size and target contrast in determining the probability of detection. Detection performance is generally poorer on the 3-inch display. Performance difference between the 3-inch display and the larger displays would be even larger in a dynamic environment. Note that the detection, recognition, and identification performance for the 6 and 9-inch displays are not significantly different. The viewing distance of 24 inc s represents the range of normally recommended distance to display s e ratio of 3:1 to 4:1. Larger displays or closer viewing may well increase the search time requirement. This discussion has assumed that the targets to be detected are typical military targets and their contrast against their background is not very large and that foveal vision is used. If a very high contrast target is present, such as luminous target against dark background, there is no size requirement for detection (although it will always be displayed at least one scan line wide) and detection may be almost immediate by the observer, even perhaps through the use of peripheral vision.

Detection scores are generally not sensitive to the resolution parameter (70).

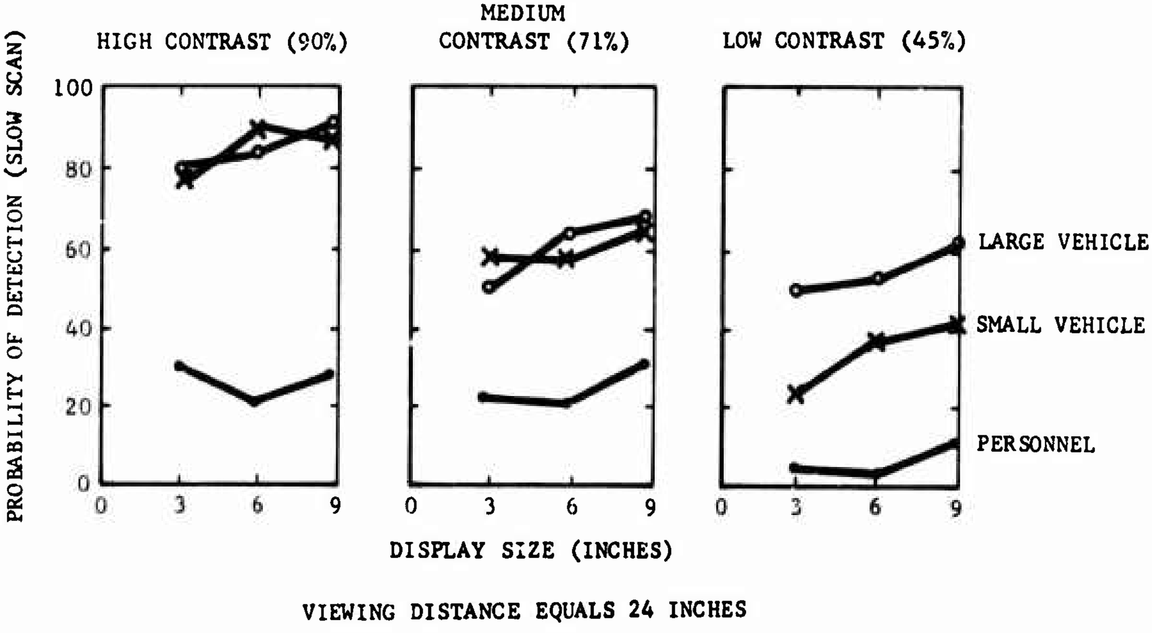


FIGURE 4.1-17. DETECTION PROBABILITY AS A FUNCTION OF IMAGE TARGET-TO-BACKGROUND CONTRAST, TARGET TYPE AND DISPLAY SIZES (70)

4.1.2.1.2 Image Motion/Search Time/Training and Briefing

The fact that the displayed scene is in motion does not degrade observer acuity performance so long as the rate of image motion relative to him does not exceed 10 degrees to 16 degrees per second (70, 51). (It is assumed that image smearing in the system is negligible.) The preferred direction for image motion is vertical (70), but this is not a strong preference. Of more concern is how long the target will remain on the sensor since the probability of detection is a function of the time available for search as long as the threshold requirements for size and contrast have been met for the particular target and environment (50). This time is determined by the imaging system field of view and relative velocity and altitude of the imaging sensor.

Several limited models for determining search time requirements have been formulated. Two of them may be found in Williams (54) and Bailey (69). Variability in search time values is high and is a function of observer subjectivity and the coincidence of observer glimpse location and target location. (Contrast and size or other cues such as target motion also enter the problem, but unless the target stands out from its background, it must be found through a search process.) One IBM study (14) reported a median detection time (unlimited time allowed), for detection after briefing, on aerial photographs of 44 seconds with a range of 15 to 148 seconds. Baker, Morris and Steedman (74) reported mean search times were from 25 to 45 seconds (in a situation where the observer knew the target existed) for display sizes ranging 1:4 to 1:3 the viewing distance. For simple targets embedded in a terrain background, Oztsaplian, et al (56) reported mean detection times of 24 seconds for a simulated briefed mission and 36 seconds for the unbriefed mode. (These data are meant to demonstrate the inherent variability in search time and the effects of briefing. They should not be construed as representative times for target search in most real-time imaging systems.) Several other researchers have reported similar results demonstrating the positive effects briefing. Krum and Farina (75) reported a 50 percent reduction in time to identify by photo-interpreters after a training course. Baker, Morris and Steedman (74) reported significant reductions in both search time and observer errors as a function of the number of sessions (Figure 4.1-18).

4.1.2.1.3 Field of View and Magnification

Items such as target type (air fields are easier to find than trucks), area covered, and magnification will also influence observer performance. The proper choice of magnification and field of view is usually a trade-off. If detection is going to occur because the adjacent background provides cues to the operator, then additional magnification (less field of view) will reduce observer performance. If however, the target is below threshold size, additional magnification will aid. There exists a point

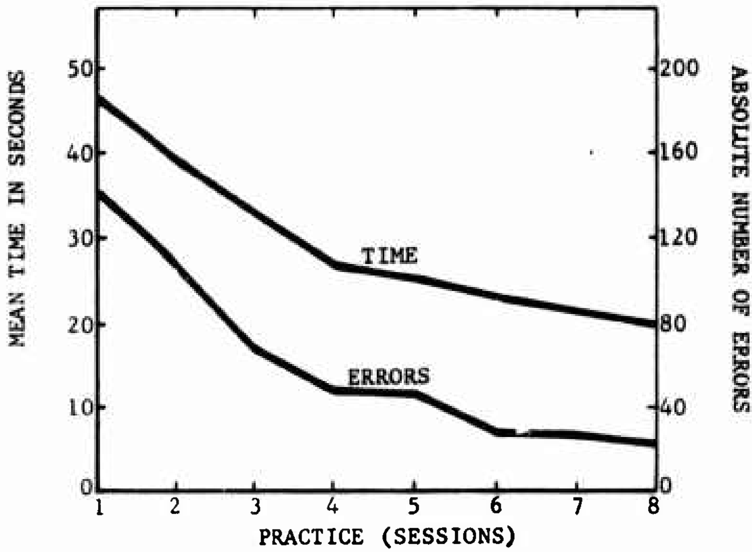


FIGURE 4.1-18. PERFORMANCE AS A FUNCTION OF PRACTICE (74)

at which additional magnification does not present additional detail to the observer due to MTF or resolution limitation of the system. Any magnification beyond that point will degrade observer performance. Most systems utilizing high magnification require also that the sight line (field of view) be stabilized to prevent image smearing. See Section 4.6.

Increased field of view usually means more clutter or detail the observer must filter through, but it also increases the probability that a target will be in the field of view.

4.1.2.1.4 Viewing Distance

When he is observing a cathode ray tube display, the viewer should sit so that his eye is at a distance between 3 and 4 times the picture height from the display. There are two reasons for this requirement. The first is that "it has been found by experiment that viewing angles of a constant scene of more than about 25 degrees in the horizontal direction causes extreme fatigue because of the constant moving of the eyeball to obtain good resolution for all parts of the scene" (114). For a standard 4:3 aspect ratio, this sets the close limit for comfortable viewing at 3 times

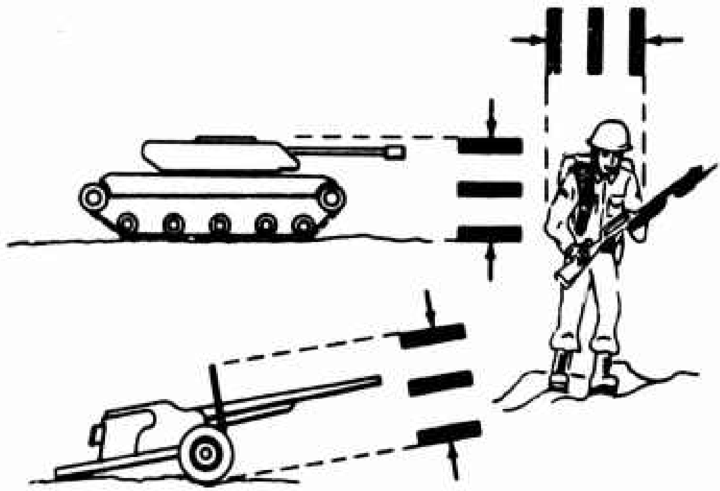
the display height. The second reason is that it is desirable to view the display at such a distance that the raster lines are not visible. Schade (7) has pointed out that "an image containing a visible line structure may appear to be sharper, but more detail becomes visible when the line structure is removed. . . . . The line structure is an interfering signal which, similar to noise, prevents detection of small detail." For a standard 525 line system, the line structure disappears at a viewing distance of 4 times the display height (115).

4.1.2.2 <u>Recognition/Identification</u>

Aside from subjective factors such as observer experience and obvious target cues (such as target movement), the physical characteristic of the target that is mostly closely linked with recognition/identification performance is the detail lying within the target boundaries. The amount of detail is abstracted to a measure of limiting resolution by determining the maximum number of resolution cells that can be resolved within the target boundaries. The resolution cells are referred to the observer resolution threshold requirements and not the absolute number of resolution elements as they might be defined elsewhere in the imaging system. Recognition may occur at detection if at that time the target size and contrast are sufficient to define the minimum number of resolution elements required for recognition. If not, it is a matter of allowing the target size to grow with time until it contains a sufficient number of resolution elements. In their study of television acquisition of targets, Ozkaplain, et al (56) noted that recognition occurred at the same point for both briefed and unbriefed targets even though detection performance was significantly different for the two cases. In both cases it was a matter of allowing the target to grow to a sufficient size that target detail could be used for recognition. In a realistic situation, a change in the system magnification can be used to enlarge the target and minimize the time required for recognition.

4.1.2.2.1 <u>Resolution Criteria for Recognition and Identification</u>

Johnson (46) has demonstrated the remarkable and greatly simplying fact that for most military targets the number of resolvable line pairs (bar patterns) required for target recognition is a constant, within 25 percent, when the number of line pairs is referenced to the <u>minimum dimension of the target.</u> Figure 4.1-19 shows the concept of applying optical cycles (line pairs) of the minimum resolution capability of the observer to the minimum dimension of the target. Figure 4.1-19 also gives the Johnson results for recognition and identification. The values of resolution for recognition are 4.0 ± 0.8 line pairs and 6.4 ± 1.5 for identification. This concept is used by Soule (34) to tabulate (Table 4.1.1) the ground resolution value required for identification of common military targets. The transformation from the target to a repetitive bar pattern is independent of contrast so long as the contrast used in the bar chart is the



TARGET	RESOLUTION PER MINIMUM DIMENSION IN LINE PAIRS	
BROADSIDE VIEW	RECOGNITION	IDENTIFICATION
TRUCK	4.5	8.0
M-48 TANK	3.5	7.0
STALIN TANK	3.3	6.0
CENTURION TANK	3.5	6.0
HALF-TRACK	4.0	5.0
JEEP	4.5	5.5
COMMAND CAR	4.3	5.5
SOLDIER (STANDING)	3.8	8.0
105 HOWITZER	4.8	6.0
AVERAGE	4.0 ± 0.8	6.4 ± 1.5

FIGURE 4.1-19. REQUIRED RESOLUTION FOR RECOGNITION AND IDENTIFICATION (46)

TABLE 4.1.1 TARGET IDENTIFIABILITY AT VARIOUS LEVELS OF GROUND RESOLUTION

		1 to 2 Feet	2 to 4 Feet	4 to 8 Feet	8 to 16 Feet	16 to 32 Feet
Aircraft	Utility A/C (C-54)	C-54	C-54	C-54	C-54	Utility A/C
	Utility A/C (L-20)	L-20	L-20	L-20	Utility A/C	-
	Fighter A/C (F-101)	F-101	F-101	F-101	Fighter	A/C
	Bomber A/C (B-57)	B-57	B-57	B-57	Bomber	A/C
	Bomber A/C (B-52)	B-52	B-52	B-52	B-52	B-52
	Helicopters (Sm and Med)	Sm or med helicopter	Sm or med helicopter	Helicopter	-	-
Vehicles	Road grader	Road grader	Road grader	Road grader	Heavy equipment	Vehicle
	Bulldozer	Bulldozer	Bulldozer	Bulldozer	Heavy equipment	Vehicle
	Semi and enclosed Trailer	Semi and enclosed tlr	Semi and enclosed trl	Semi and enclosed trl	Large truck	Vehicle
	Tank truck	Tank truck	Tank truck	Tank truck	Vehicle	-
	2-1/2-ton truck	2-1/2-ton truck	2-1/2-ton truck	2-1/2-ton truck	Large truck	
	Jeep	Jeep	Jeep	Small truck	Vehicles	-
	Railroad vehicle	Boxcar, flatcar, etc.	Boxcar, flatcar, etc.	Boxcar, flatcar, etc.	Railroad vehicle	Railroad vehicle
	Tank (light, med, heavy)	Lt, med or hvy tank	Lt, med or hvy tank	Tank	Tank	Tank
Weapons	Man carried weapon	-	-	-	-	-
	Vehicle mounted 105 and 155 mm	105 or 155 mm rec rifle	105 or 155 mm rec rifle	Vehicle mounted weapon	-	-
	Towed weapon	8-inch gun	Towed weapon	-	-	-
	Howitzer	8-inch howitzer	8-inch howitzer	Towed weapon	Towed weapon	-
	GNC Launch missile	GND launch missile	GND launch missile	GND launch missile	-	-
	Air launch missile	Air launch missile	Air launch missile	Air launch missile	-	-
Miscellaneous	Tent (10 man and hospital)	Tent	Tent	Tent	Tent	-
	Jet engine test area	Jet engine test area	Jet engine test area	Jet engine test area	Complex	Complex
	Fuel dump					
	Airfield	Airfield	Airfield	Airfield	Airfield	Airfield
	Road (improved)	Road	Road	Road	Road	Road
	Troops	Troops*	Troops*	-	-	-
	Railroad tracks	Railroad tracks	Railroad tracks	Railroad tracks	-	-
	Bridge	Bridge	Bridge	Bridge	Bridge	Bridge
	Dam	Dam	Dam	Dam	Dam	Dam

-No identification possible

*Under some conditions

same as that of the target. Since system resolution performance improves as contrast is increased, a higher contrast target will be more recognizable than a lower contrast target of the same size.

It is sometimes necessary to extend or modify the Johnson results even though the general use of a resolution cell transformation holds. For example, the Johnson criteria of using the minimum target dimension would lead one to the conclusion that a ship with a height above water as the minimum dimension would be equally detectable from the bow and side aspect. One possible extension is to use an area model instead of a bar pattern model. The subject is treated further in Paragraphs 4.7.2.2 and 4.7.2.5. See also Section VI of Rosell and Willson (41).

The Erickson (77) result that 20 active scan lines per target dimension for TV identification of real targets can be reconciled with the Johnson criteria. With high contrast targets in a noise free display the relation between the number of scan lines and vertical resolution (in TV lines) is the Kell factor (48) which is usually taken to be about 0.7 times the number of active lines. The Erickson result is then 14 TV lines for identification or 7 line pairs (compare to 6.4 ± 1.5 line pairs).

4.1.2.3 Image Quality

The subject of image quality has already been discussed as it relates to spatial frequency (Section 3.3). This section will be concerned with the definitions of image quality, supporting test results and effects of noise on image quality and the demand modulation function.

Schade introduced the concept of "equivalent number of lines" designated N_e. It is related to the system MTF (see Paragraph 3.3.3) by

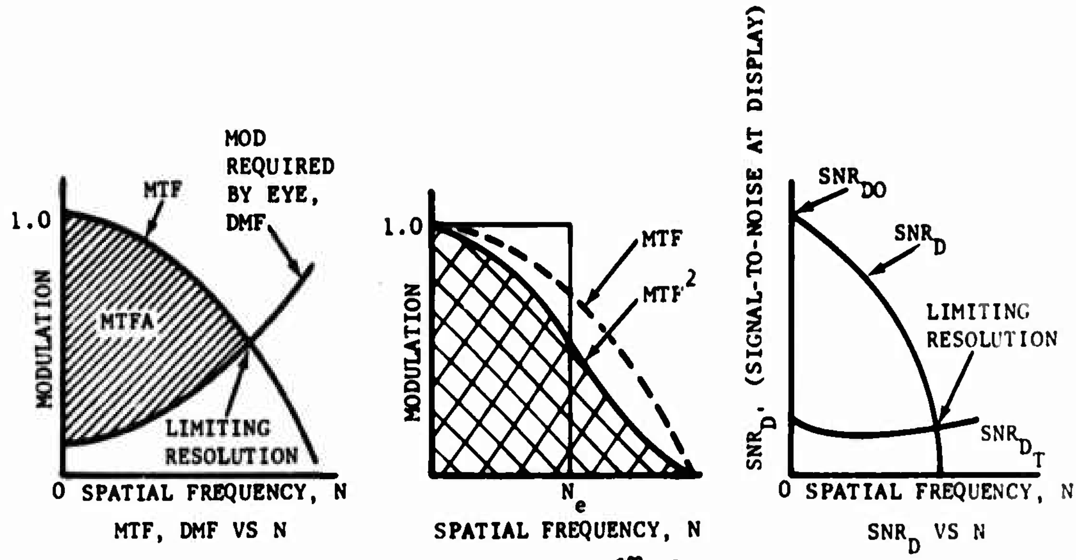
$$N_e = \int_0^\infty (MTF)^2 \, dN \qquad (4.1\text{-}1)$$

where

N_e is in TV lines/frame, and

N is in TV lines/frame.

This relation can be interpreted as shown in Figure 4.1-20. N_e is the spatial frequency value which would define a square bandpass of unit amplitude. An alternate criterion is MTFA (Figure 4.1-20) which is the area between the Y axis, the MTF curve, and the demand modulation function (see also Paragraph 3.3.4). Studies conducted by the Boeing Company (78) on photographs with controlled MTFA values demonstrated that the



$$A = N_e \cdot 1 = \int_0^\infty MTF^2 dN$$

N_e	EQUIVALENT LINE NUMBER
MTF	MODULATION TRANSFER FUNCTION
DMF	DEMAND MODULATION FUNCTION
N	SPATIAL FREQUENCY, TV LINES/PICTURE HEIGHT
SNR_D	DISPLAY SIGNAL-TO-NOISE RATIO
SNR_{DT}	DISPLAY SIGNAL-TO-NOISE RATIO, THRESHOLD
SNR_{DO}	DISPLAY SIGNAL-TO-NOISE RATIO AT ZERO SPATIAL

FIGURE 4.1-20. IMAGE QUALITY MEASURES

MTFA value was positively related with subjective estimates of image quality and objective measures of observer performance.

For television and FLIR type sensors, Rosell (26) has developed the concept of the SNR_D or signal to noise ratio at the display. The area between this curve, the Y axis, and the observer threshold curve over all spatial frequencies is related to the MTFA. The observer threshold curve in this instance is expressed in terms of the threshold value of the display signal to noise ratio.

4.1.2.4 Noise Effects

Image noise, whatever its source, affects the recognition process. It increases the congestion of the scene, reduces contrast and distorts contrast boundaries. When working with LLLTV and FLIR systems, the observer threshold requirement will often be determined by noise considerations rather than contrast limitations of the eye. Coltman and Anderson (1) performed a classic work in which they demonstrated that the detection of periodic sine wave intensity pattern in white noise (Section 3.4) is a linear function between rms signal to rms noise and spatial frequency of the sine wave pattern. Their results are shown in Figure 4.1-21. The discontinuity at lower spatial frequencies is attributed to the effects of the finite display size. The results can be used to predict limiting resolution of sensors where the resolution performance is white noise limited and the signal and noise characteristics are known as a function of scene radiance. Rosell (61) has done additional work in determining the detection thresholds of the observer for simple aperiodic targets and periodic charts. Rosell's threshold values are determined for the conditions of white noise and sufficient display illumination such that the observer is S/N limited rather than resolving power limited due to a low value of display luminance. Rosell's values for S/N, called SNR_D, refer to observed values of displayed (area) peak signal to rms noise. The threshold values of SNR_D for squares and rectangles are shown in Figure 4.1-22. The SNR_D required for a given probability of detection is the same for a large range of area and length to width ratios. The relation for SNR_D for these aperiodic images is

$$SNR_D = \Delta(t_e\ a)^{1/2}\ SNR_v \qquad (4.1\text{-}2)$$

where

Δ is a constant dependent upon display aspect ratio, number of active scan lines per frame height and video bandwidth;

t_e is the eye integration time (0.2 second);

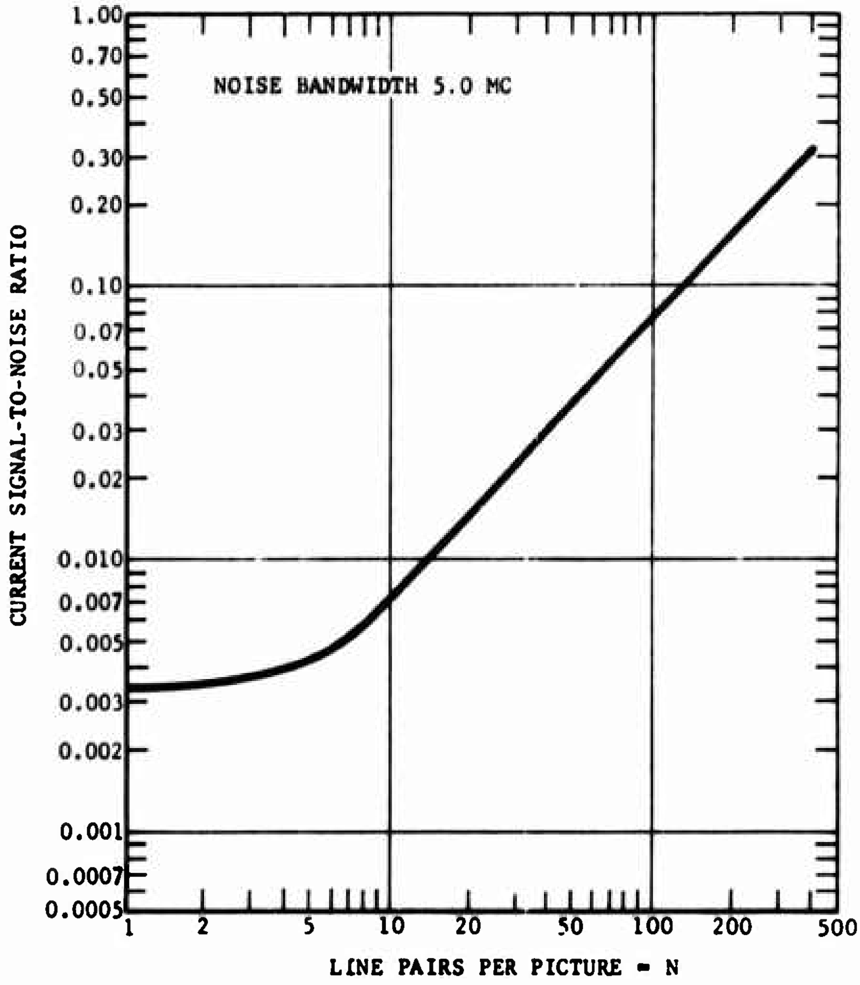


FIGURE 4.1-21. THRESHOLD SIGNAL-TO-NOISE RATIO AS A FUNCTION OF NUMBER OF CYCLES OF THE SINE WAVE BAR PATTERN DISPLAYED (1)

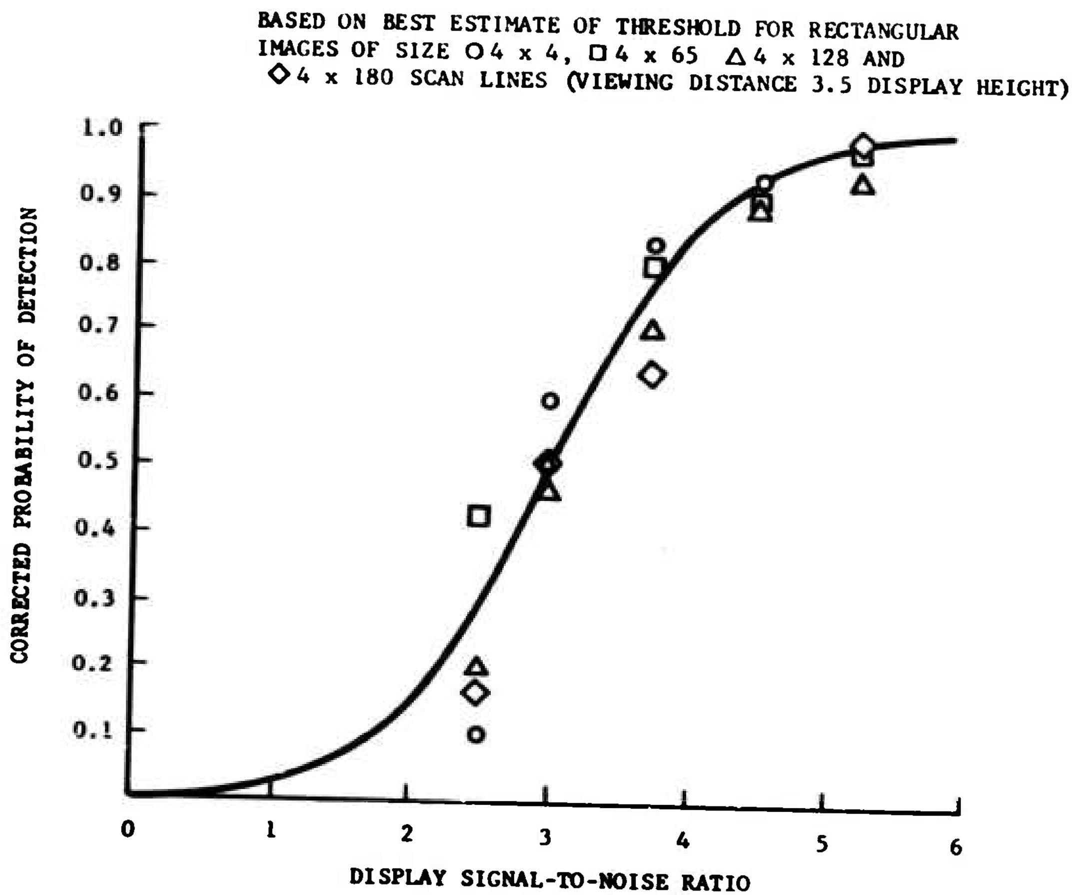


FIGURE 4.1-22. MEASURED VERSUS PREDICTED PROBABILITY OF DETECTION (61)

a is the displayed image area in number of square scan lines;

SNR_v is the video signal to noise ratio for an image which is large compared to the impulse response of the system.

(See also Paragraph 4.7.2.5.1 for application of these relationships to system analysis.)

From Figure 4.1.22 it is clear that the threshold value for SNR_D (SNR_{D_T}) for high detection performance should be between $SNR_{D_T} = 5$ and $SNR_{D_T} = 6$.

Rosell has extended the SNR_D concept to include periodic bar targets. Any periodic description of SNR_D must be concerned with the spatial frequency response of the system. The display S/N ratio per element (or single bar) for large length to width ratios is

$$SNR_{D/E} = \left[t_e \, \Delta f/b \right]^{1/2} \left[\frac{\tilde{r}\,(N_{TV})}{N_{TV}} \right] SNR_v \qquad (4.1\text{-}3)$$

where

Δf is the video bandwidth,

b is the display aspect ratio,

N_{TV} is the lines per picture height,

$\tilde{r}\,(N_{TV})$ is the system MTF.

This relationship can be used to predict the limiting resolution of systems as long as the length to width ratio requirement is met.

When thresholds of detection of bar patterns by observers are considered (the demand modulation function in noise), the effects of length to width ratio of the bars cannot be ignored. The limiting resolution model of Equation (4.1-3) must be modified to account for the ability of the observer to spatially integrate in two dimensions. An area model meets this requirement and the elemental SNR_D detection threshold can be related to a bar area threshold which involves the bar length to width ratio.

$$SNR_{D/ET} = SNR_{D/A\text{-}T} \, (\ell)^{-1/2} \qquad (4.1\text{-}4)$$

where

$SNR_{D/A-T}$ is the threshold detection value of signal-to-noise from the area model, and from the aperiodic model is equal to 5.3,

ℓ is the bar length to width ratio.

$SNR_{D/E-T}$ as a function of ℓ is plotted in Figure 4.1-23. For large length to width ratios (20:1) $SNR_{D/E-T}$ is about 1.2 which confirms the threshold detection results of others for periodic bar patterns. Equation (4.1-3) can be used to define limiting resolution if the proper value of $SNR_{D/E-T}$ dependent upon ℓ is used.

A consequence of the results depicted in Figure 4.1-23 is that the Coltman/Anderson assumption that only 7 line pairs are used in making an identification is somewhat suspect. Rosell concludes this assumption cannot be supported, and that it was the restriction of bar height by Coltman and Anderson that produced the results that they interpreted for the 7 line pair requirement.

Rosell's SNR_D models introduce quantitative measures of image information content. Along with transforms to real word images such as the Johnson criteria, they form a basis for defining observer requirements in the presence of noise in a quantitative manner. Future work in this area will determine the degree of applicability of these models.

4.1.2.4.1 MRT (See Also Paragraph 4.7.2.7)

One technique used in the evaluation of FLIR systems is to use a thermal target with a 4-bar resolution pattern that is viewed by the observer on the display. When the system is operated in a high gain (noise limited mode) and the bar length to width ratio is 7:1, the resulting minimum temperature differential in the target for detection versus bar pattern spatial frequency is called the MRT curve. It gives a measure of spatial frequency performance of the observer for a noise limited system and is an empirically determined demand modulation function for that observer and that system. The MRT can be related to SNR_D or other measures of FLIR threshold performance.

4.1.2.4.2 Noise Frequency Content

Both the Coltman/Anderson and Rosell results are for white noise (equal noise power per cycle of bandwidth) which for photon limited systems, such as FLIR's or highly intensified LLLTV systems, is accurately descriptive of the limiting noise. The amount of perceived noise is a function of the

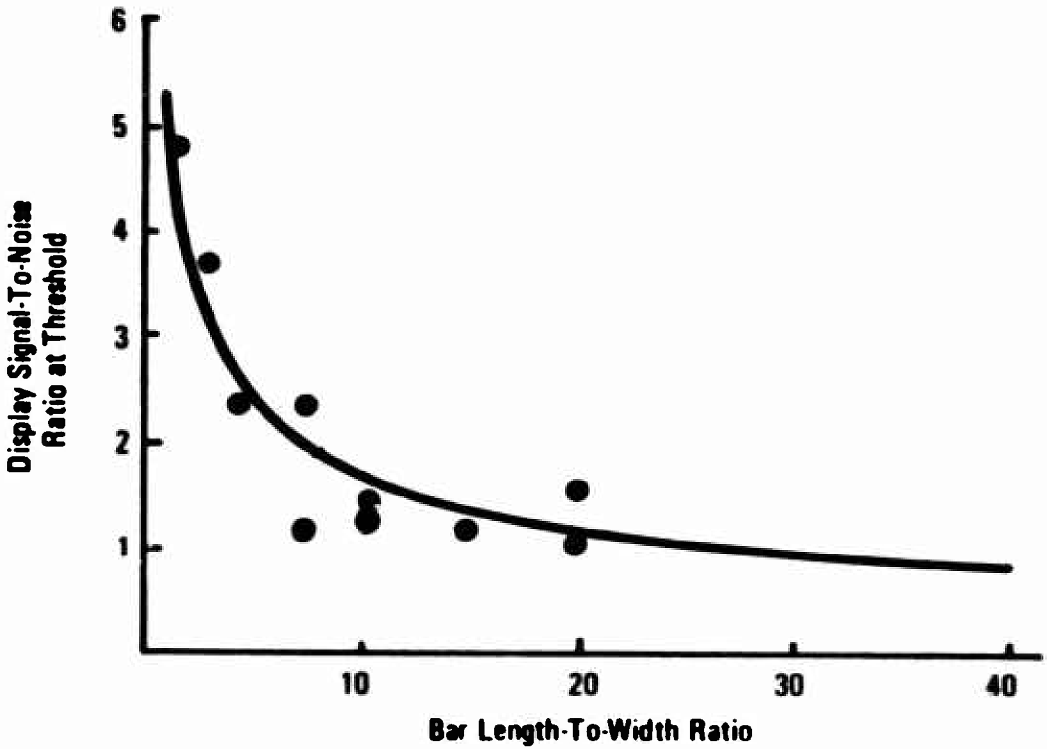


FIGURE 4.1-23. PER ELEMENT DISPLAY SIGNAL-TO-NOISE RATIO AT THRESHOLD REQUIRED TO IDENTIFY BAR PATTERNS AS A FUNCTION OF BAR LENGTH TO WIDTH RATIO. DATA POINTS FROM COLTMAN/ANDERSON (61)

noise bandwidth of the system up to the point that the observer's eye provides the bandwidth limitation. Video signal to noise ratios of 25:1 or larger are required for acceptable images (34).

For equal signal-to-noise ratios, noise with different spatial frequency spectra will be perceived somewhat differently by the observer. The threshold values for observer detection in noise are then a function of the noise frequency spectrum and should be adjusted accordingly. Generally high frequency fine grained noise is less bothersome than the white noise of photon or shot noise limited systems.

Phosphor characteristics of the display CRT can minimize noise effects (Soule (34)), but picture smear due to scene movement can limit the degree to which the phosphor time constant can be extended.

4.2 THE DISPLAY

Subsection 4.2 discusses one of the components of the real time imaging system - the observers display. Observer requirements are covered in Section 4.1. The common types of displays are presented, and the most common display element, the cathode ray tube is described in some detail. Display performance requirements are discussed as they apply to field usage.

4.2.1 DISPLAY TYPES

a. Direct View Cathode Ray Tube (CRT). The most common display is the cathode ray tube (CRT) which is directly viewed by the observer. This is the same display mechanism used in commercial television receivers.

b. Heads-up-Display (HUD). This display usually uses a CRT of sufficient brightness that the display face can be projected onto a combining glass that enables the observer to view the imaged scene as though it were located in space. It allows the observer to view the projected image simultaneously with a distant directly viewed scene, or it may allow the observer the illusion of looking directly at a scene as might be the case with a nighttime system (Figure 4.2-1).

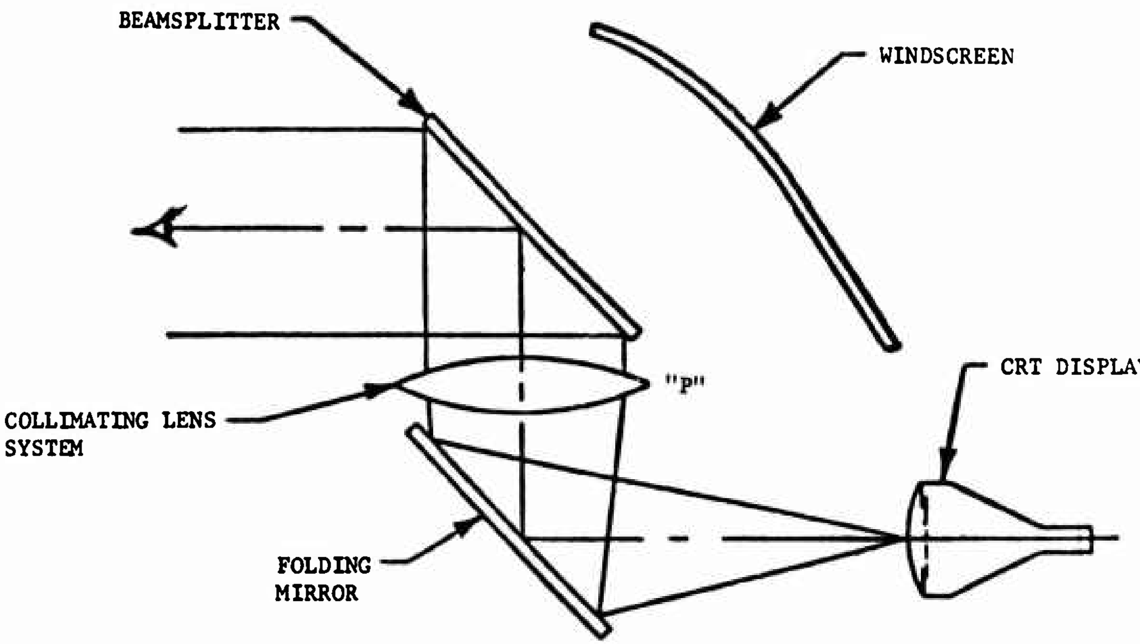


FIGURE 4.2-1. GENERAL OPTICAL LAYOUT OF HEADS-UP DISPLAY

c. Helmet Sight. One common type of helmet sight uses a small CRT and combining optics to form an image, normally collimated, for one of the observer's eyes. The other eye is unobstructed and the observer is free to direct his vision as he chooses and the displayed image remains superimposed upon the viewed scene. The orientation of the observer's sightline can be used to input target coordinate information to a computer (Figure 4.2-2).

d. Multisensor Displays. Different sensor outputs are often presented on the same display, often with different display requirements. It is common for an electro-optical imaging system display to be shared with a radar display where the framing or persistence requirements differ significantly. In this case, the phosphor and the writing beam (gun) of

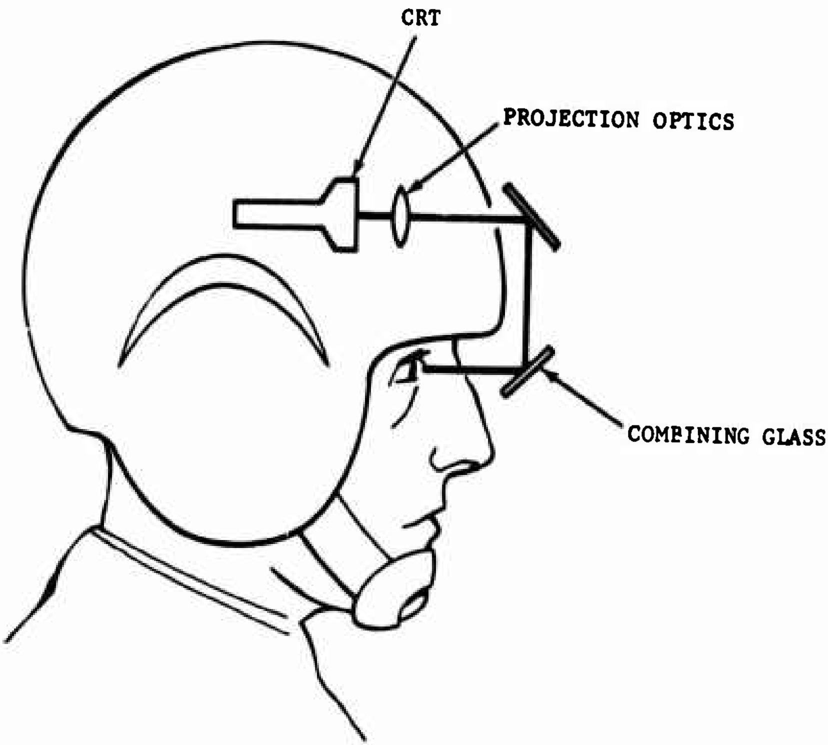


FIGURE 4.2-2. SCHEMATIC - HELMET SIGHT DISPLAY

the display tube are designed for imaging use and an auxiliary means is employed to retain or increase the persistence for the radar display. One means is to store the radar image in an auxiliary device such as a two-gun scan converter and use a normal CRT display to read out the stored radar image. The imaging system signal can then by-pass the storage device when a real time imaging display is desired. Another common means is to add additional components to a CRT such as a flood or viewing gun and a target storage mesh, and the CRT tube itself can become a storage device. By varying the rate that the target information is changed, one can create persistence as required. Such compound CRT's are called Direct-View Storage Tubes (DVST).

e. Direct View Devices/Eyepieces. When using image intensifiers or image converters and especially where lightweight and portable features are desired, the observers will view directly the luminous output of the final intensifier stage. When the final stage is small, such as 25mm diameter phosphor surface, an eyepiece with a wide field of view is normally used to magnify the screen to give an apparent size to the viewer significantly larger than the actual screen. A recent development in intensifiers is the large output phosphor surface which can be obtained in sizes up to 5 inches. There is a brightness loss compared to the small tube with eyepiece.

f. New Display Techniques. Methods for providing brighter displays for ambient daylight use with sufficient resolution are under development. One possibility is a modulated array of photo emitting diodes.

4.2.2 DESCRIPTION OF THE CATHODE RAY TUBE

4.2.2.1 The Cathode Ray Tube

The CRT is a thermionic (electron emission through a heated element) vacuum tube wherein the electron tube current from the thermionic source is modulated with the video or picture information and the resultant beam is scanned across and focused onto a phosphor screen. The modulated beam is converted in the phosphor into a radiant spot which varies with the modulation of the beam. The elements of one type of CRT are shown in Figure 4.2-3. (The other common means of deflecting and focusing the electron beam is with magnetic coils.) In this tube the electrons are boiled from the cathode and are accelerated toward the phosphor screen. The beam passes through the control grid which modulates (increases and decreases) the beam current with the signal video. The next grid accelerates the electrons and then the beam is focused for the proper spot size on the phosphor screen. The final stage is the deflection stage which directs the beam in the required scanning pattern.

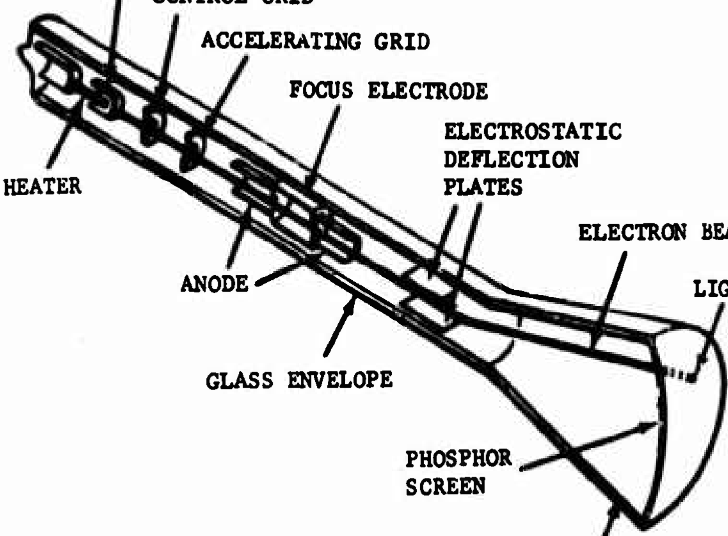


FIGURE 4.2-3. SIMPLIFIED CRT SCHEMATIC (ELECTROSTATIC FOCUS AND DEFLECTION) (80)

4.2.2.2 The Scanning Pattern or Raster

The raster requirements are determined by the sensor portion of the system. In the case of the television sensor where the target image in the tube is read out in serial fashion with a scanning electron beam, the display scan pattern is a one-to-one reproduction (barring the case of scan conversion) of the camera tube scanning pattern. In the case of a FLIR system where the detector array presents several scanning spots, a scan conversion to serial video for the display is accomplished through either electronic or electro-optical multiplexing. The video signal in either case is a time representation of the scene contrast as it was scanned by a small aperture. That video signal is impressed upon the control grid of the CRT; and if the electron beam of the CRT is scanned in similar fashion to the sensing aperture of the sensor, there will be reproduced on the CRT phosphor an image of the scene contrasts for that scan line. (The reproduced image is of course subject to both the amplitude and spatial transfer functions of the system.) Several of these scans are made in an orderly fashion across the target scene and reproduced one for one on the CRT phosphor screen where

the persistence of the phosphor allows the observer to see the reconstructed image. The time that it takes to accomplish one complete scan of the field of view on the target scene is called the frame time. Figure 4.2-4 depicts the most common scanning pattern. This is not a recommendation but merely an example of what is typically done. The scanning requirements should be determined as part of the systems analysis (Section 4.7) and should consider required display resolution, system bandwidth allocations, critical fusion frequency and ambient lighting conditions. Figure 4.2-4 shows a scanning pattern where the field of view is covered twice in the completion of one scan of the field of view. The single incomplete scan is called a field. When more than one field is used to complete the frame, the scanning pattern is said to be interlaced. Figure 4.2-4 depicts a 2:1 interlace (2 fields per frame) but larger values of interlace are possible. The use of interlace keeps the flicker frequency high (above the CFF) while preserving system bandwidth.

Another descriptor of the scanning pattern is the number of scan lines used. Common values are 525 (commercial television), 875, 945, and 1025 lines per frame. This is the total number of scan lines that one achieves by dividing the frame time by the period from the beginning of

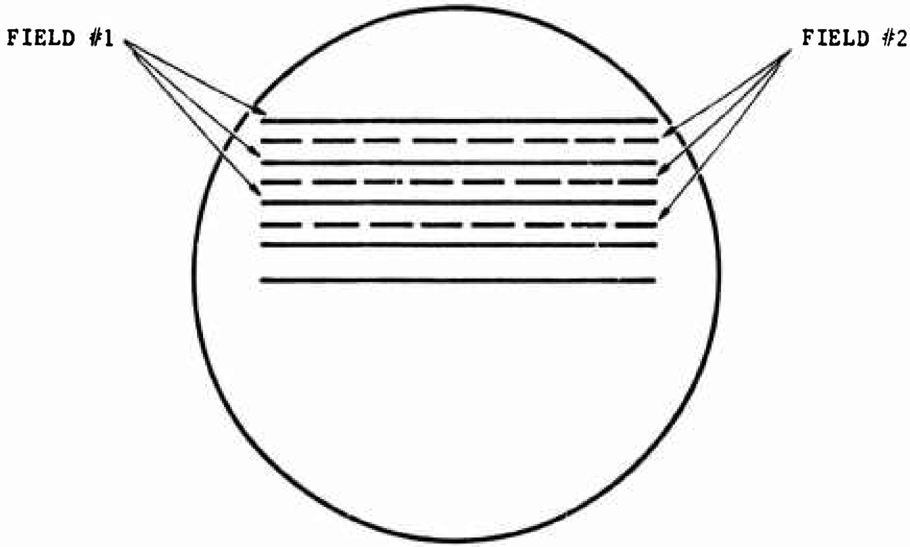


FIGURE 4.2-4. CRT SCAN PATTERN 2:1 INTERLACE

one horizontal scan to the beginning of the next. It is not the number of active scan lines witnessed on the display face. Some of the scanning time (and hence a number of scan lines) is consumed in retracing the beam in preparation for the next field or frame. Visible scan lines are called active scan lines. For a 525 line system the number of active scan lines is approximately 490 lines. The number of scan lines and spot size (or sampling rate) of the display must be chosen to meet the sampled data frequency restrictions defined to avoid alias signals on the display (Paragraph 3.4.3.1 and Paragraph 4.7.3). (Note: A FLIR display format may differ considerably from that of television, but generally the same considerations apply. See Paragraphs 4.5.4 and 4.7.3 for related FLIR format considerations.)

4.2.2.3 The Phosphor

The important variables of a phosphor for real time viewing are:

(1) Color (or characteristic)

(2) Grain

(3) Brightness (as an absolute level and as a conversion efficiency from the beam input)

(4) Persistence

Color is usually not an overriding consideration but white phosphors give a more normal presentation to the observer. It is common to describe the color qualities of a CRT phosphor as its characteristic such as a P-4 characteristic. The characteristic as a description of spectral property may be used with other phosphors or mixes of phosphors to define their spectral output.

Grain size has an effect upon the ultimate resolution capability of the tube. For large displays it may not be a consideration.

The brightness of a CRT is a function of more than the phosphor type. It is a function of screen design, scanning speed of the spot (dwell time), accelerating voltage and beam current, and phosphor characteristics. The upper limit to useful display brightness is primarily a function of the loss in MTF accompanying higher beam currents rather than in any limitations imposed by the phosphor in the radiant conversion process.

The persistence, or radiant decay time, of the phosphor is chosen such that flicker is minimized (long decay times minimize the CFF) consistent with the requirement that the display not introduce smear resulting from scene movement across the display. This requirement implies the decay time must be faster than the eye storage time (Paragraph 4.1.1).

The most common phosphors for fast frame rate and high visibility displays are the medium (1 millisecond to 100 milliseconds) to medium short (10 microseconds to 1 millisecond) persistence high efficiency sulfides. The more common ones are:

Phosphor	Color	Power Factor (lumen/electrical watt for average beam conditions)
P-4	White	4.7
P-31	Green	50.6
P-20	Yellow/Green	65.1

4.2.3 DISPLAY PERFORMANCE CONSIDERATIONS

Note that CRT resolution (MTF) performance, brightness performance, and contrast performance are interrelated and must in general be considered together along with such external factors as observer viewing distance, screen size, and ambient illumination levels.

4.2.3.1 Brightness and Contrast Performance

The brightness of the display should be sufficient to give the observer sufficient contrast range for the ambient light level in which he is working (hopefully 7 to 9 shades of gray* corresponding to brightness ratios of 11:1 and 23:1) and to remove any resolution limitation of the observer due to the displayed luminance of the image. Any brightness increase over this level may result in MTF degradation of the display (Paragraph 4.2.3.2).

CRT's can be obtained with peak brightness outputs from 1000 to 2400 foot-lamberts but one should consider resolution performance of the tube at those levels.

The more common upper limits for CRT displays are from 40 to 100 foot lamberts. Miniature CRT's for use with the helmet sight are capable of 50 foot lamberts at 1000 lines of limiting resolution. (39)

One to ten foot-lamberts is generally sufficient brightness for night time viewing. Daylight requirements for brightness depend upon the ambient illuminance levels falling on the display. In open shade the illuminance

*A shade of gray or gray level here refers to a logarithmic-scale in which brightness values are measured in discrete steps with a ratio value between steps of the $\sqrt{2}$. The scale reference is the minimum brightness level on the display.

on a bright day is about 1000 foot-candles. If one ignores specular reflection of the sky background from the faceplate of the CRT and considers only the diffuse reflection from the phosphor screen, the low brightness value for 10 percent reflection is 100 foot-lamberts. To get 7 shades of gray the display high lights must be at least 1200 foot-lamberts. If the display is located in direct sunlight (10,000 foot-candles) the high light brightness is for 7 shades 12,000 foot-lamberts - an impractical value and devices such as sun shades must be employed.

The contrast available from a CRT is limited by one of two mechanisms. The one, previously discussed, is the reflection of ambient illumination. The other results from light scattering from the scanning spot in the CRT itself. This mechanism provides the ultimate limit to CRT contrast performance which is usually from 20:1 to 30:1 (8 to 10 gray shades). For a display with an inherent range of 9 gray shades and a minimum brightness level of 1 foot lambert, ambient radiation causing a reflected minimum of 5 foot-lamberts will reduce the contrast range to 5 gray shades. For this reason consideration is given to display filters which minimize the transmission of ambient light to the phosphor screen and other CRT optical surfaces.

4.2.3.2 Resolution Performance

Resolution capability of the CRT is primarily determined by the spot size of the electron beam. Specifications for CRT's spot sizes should sometimes be subject for close examination. The measured value for spot size is a function of the technique by which it is measured. Most of the resolution data is in terms of limiting resolution but MTF data is becoming available. MTF data as a function of beam current or display brightness is required to adequately define the system performance over the ambient environmental conditions of the observer.

Limiting resolution may be in terms of lines per frame height or lines per inch of display. Commercial tubes expect a limiting resolution of 500 to 1000 lines per frame height and this is done with spot sizes ranging from 20 to 50 mils. (This is roughly equivalent to 40 to 100 lines per inch). Military tubes can achieve 200 lines per inch easily and high resolution tubes can go beyond this. At some point however any gain in resolution is bought at the expense of brightness as the spot size must be held small. As the spot size is a function of beam current, the spot size is a function of display brightness. In a conventional tube the spot size may change by a factor of 2 by adjusting the display brightness. Figure 4.2-5[70] shows the effect of doubling the spot size on the display MTF of a CRT for various values of spot sizes where the spot intensity distribution is assumed to be Gaussian and the spot diameter is the 50 percent amplitude point.

High resolution CRT's are often of such a design as to be impractical for military applications. They may require sophisticated electronics, be relatively fragile and oversized.

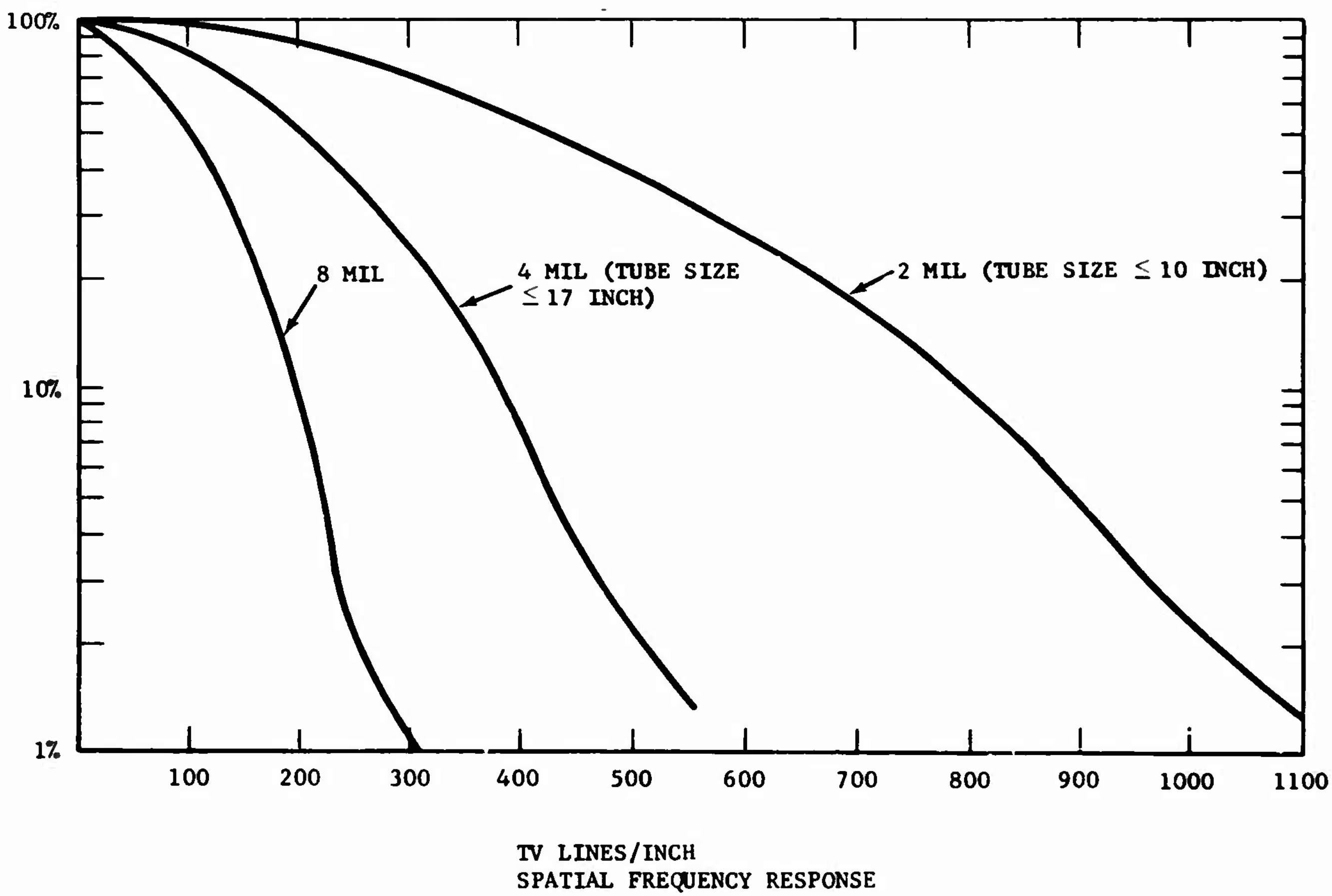


FIGURE 4.2-5. CRT MTF AS FUNCTION OF SPOT SIZE (SPOT SIZE DEFINED AT THE 50-PERCENT NORMALIZED AMPLITUDE OF GAUSSIAN POINT SPREAD FUNCTION) (70)

4.2.4 MISCELLANEOUS DISPLAY CONSIDERATIONS

4.2.4.1 Signal Processing

The system engineer may wish to include as part of the display electronics processing for γ or brightness distortion resulting from the sensor. Aperture correction may also be inserted at this point.

4.2.4.2 General Considerations

In addition to the performance factors already discussed, one should also consider the operating environment, number and type of display controls, optimum display size for viewing conditions (see Paragraph 4.1.2.1.4), and amount of picture distortion that can be accepted. Resolution and distortion performance are always better at the center of the CRT than at the edges, and it is customary to provide different performance specifications for these areas.

4.2.4.3 Comparison of the Helmet Sight, Heads Up Display and the Direct View CRT

	Advantages	Disadvantages
Direct View CRT	Simplicity Binocular vision Variable viewing distance and hence variable magnification	Heads down attitude for observer Requires eye accommodation from distant viewing Subject to solar washout
HUD	Virtual object is at infinity hence no eye accommodation problems Heads-up attitude	Not enough display brightness for daylight use More complicated and difficult to install
Helmet Sight	Requires little space No specific head attitude required Virtual object at infinity, hence no eye accommodation problem Minimum daylight washout	Binocular vision problem Adds weight to observer's head (objectionable in high g environments)

4.3 THE TARGET IN ITS ENVIRONMENT

Subsection 4.3 considers the radiant properties of the target, background scene, the environment, including the atmosphere, and ambient illumination which determines those properties. Natural and artificial illumination sources, which are the prime determinants of the radiant signal for TV type sensors, are discussed. A quantitative description of contrast is presented. The self-radiating blackbody properties of the scene used by FLIR sets are discussed. Transmission properties of the atmosphere for visible, near and middle infrared portions of the radiation spectrum are presented.

4.3.1 GENERAL

In the imaging system it is the irradiance (see Appendix A) of the target image upon the radiation transducer (sensor) that is the primary determinant of imaging system performance. The irradiance in turn is a direct function of target radiance (intensity per unit area) as is demonstrated in Section 4.4.2. In the case of television and intensifier systems the target radiance is determined by the radiation from natural or artificial sources incident upon the target and from the reflectance characteristics of the target. FLIR systems depend upon the temperature dependent radiance of the target itself to generate sufficient target signal for imaging purposes (3.1). For any system type the intervening atmosphere will affect the resultant scene irradiance at the sensor.

Target size and spatial frequency content are also significant target qualities which determine imaging system and observer performance. The background; which determines target contrast noise levels, and number of conflicting and competing images; must also be considered for its effect upon discrimination performance.

There are obvious target clues, such as target motion and bright light sources, which are also considerations which will only be mentioned.

4.3.2 ILLUMINATION

4.3.2.1 Natural

The four natural sources of light for photoelectronic imaging are the sun, the moon, the stars and airglow. Figures 4.3-1 and 4.3-2 show the relative illuminance (photometric system) values at the earth's surface for these sources. In Figure 4.3-2, the angle, ϕ_e, is the angular distance of the moon from the sun with the earth as the reference apex of the angle. While these figures are valid for comparison of available light from the

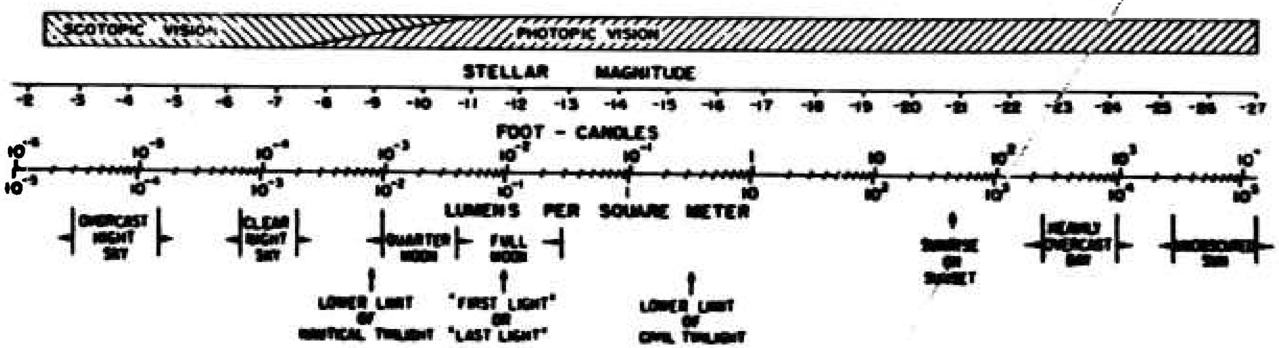


FIGURE 4.3-1. RANGE OF NATURAL ILLUMINANCE LEVELS (16)

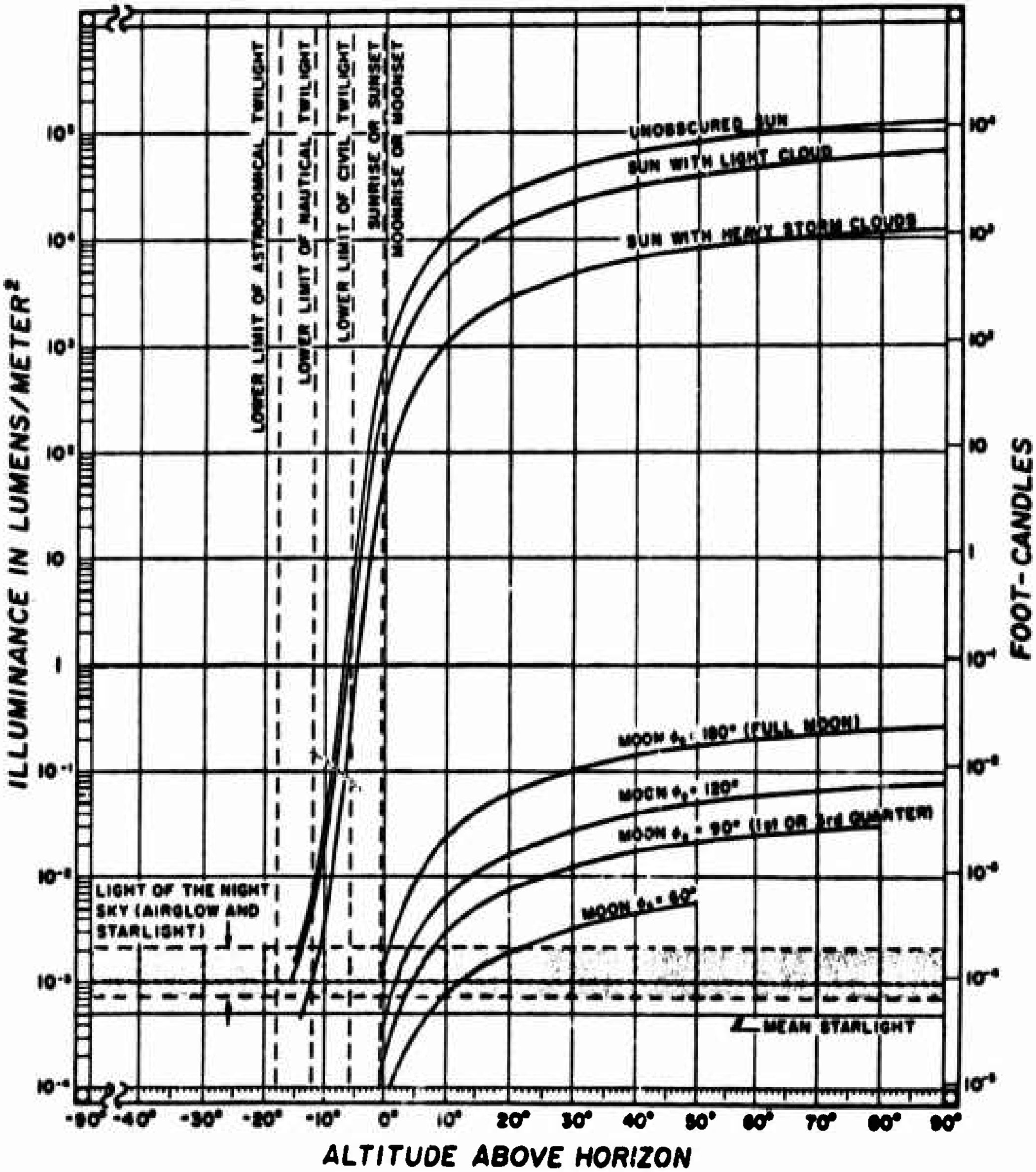


FIGURE 4.3-2. ILLUMINANCE LEVELS ON THE SURFACE OF THE EARTH DUE TO THE SUN, THE MOON, AND THE LIGHT OF THE NIGHT SKY (81)

various sources, the appropriate measure for use in determining the sensor response is the spectral distribution of radiant energy (see Appendix A).

4.3.2.1.1 Solar Radiation

The sun as a radiation source is approximately a 6000 K blackbody as modified by any intervening atmosphere. The atmosphere will modify both the spectral content and the total amount of solar radiation reaching the earth's surface. The atmosphere does this by scattering light from its incident direction and absorbing portions of the available solar radiation. In either case a portion of the lost radiation will reach the earth as skylight. The amount of scattering and absorption depends upon types and size of scattering centers and the chemical constituency of the atmosphere. The constituency of the atmosphere is not constant as the amounts of water vapor change periodically, and ozone and CO_2 concentrations may depend upon geographical factors.

For a given atmospheric constituency the factor that most determines the amount of solar radiation reaching the earth's surface is the radiation path length through the atmosphere. This is in turn a function of the position of the sun. The sun location is normally measured from the normal to the earth's surface and the departure of the sun from this normal position is called the zenith angle. Figure 4.3-3 gives the incident solar energy as a function of wavelength and atmospheric path length for a particular atmospheric constituency. The unit used for path length is the air mass. When one looks straight up at the sun from the earth's surface, he is looking through one air mass. As the sun moves from this position, the path length increases as the secant of the zenith angle up to the point that atmospheric bending of the light rays (called refraction) forces a deviation from this relationship. (See Figure 4.3-4 for illustration of the zenith angle.)

4.3.2.1.2 Skylight

As the amount of solar radiation is a function of the atmospheric constituency, so is the skylight. Daytime skylight consists of scattered solar radiation, emission from absorbed solar radiation and reflected terrain radiation which is also scattered, absorbed, and emitted. Skylight depends upon the type of atmospheric scattering, amount and types of cloud covering, solar zenith angle, and type of ground reflection. On relatively clear days the skylight spectral distribution is rich in blue and ultraviolet until the sun is low on the horizon, and then the spectral emphasis shifts toward the red. Figure 4.3-5 shows the sea level irradiance from a clear sky as a function of solar angle and wavelength. On a very clear day, the scattering mechanism is Rayleigh scattering which means the scattering particles or centers are small compared to the wavelengths of light.

The more general scattering theory (see Reference (83) is the Mie theory which can handle larger particle sizes as long as the optical properties of the scattering particles are known.

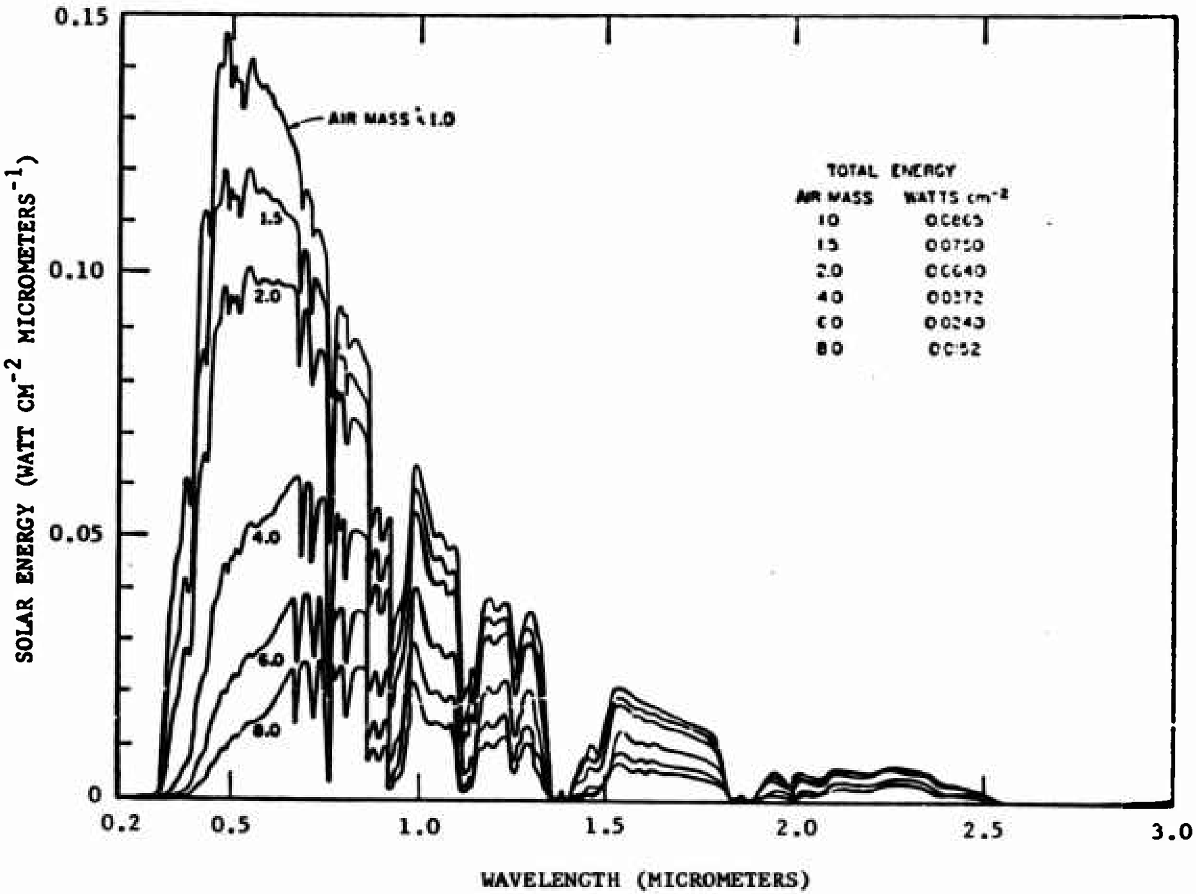
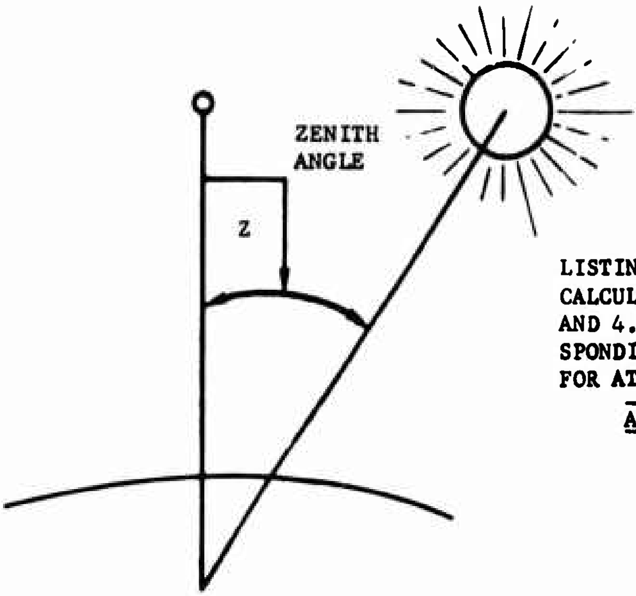


FIGURE 4.3-3. SPECTRAL DISTRIBUTION AS A FUNCTION OF WAVELENGTH OF DIRECT SOLAR RADIATION INCIDENT AT SEA LEVEL ON A SURFACE PENPENDICULAR TO THE SUN'S RAYS FOR SLANT PATHS OF AIR MASS 1.0 TO 8.0. CONCENTRATION OF PRECIPITABLE WATER, 10 MILLIMETERS; OF AEROSOL, 200 PARTICLES PER CUBIC CENTIMETER; OF OZONE, 0.35 CENTIMETER (82)



UP TO Z = 72,
AIR MASS = SEC Z

LISTING OF AIR MASSES USED FOR THE CALCULATIONS ON WHICH FIGURES 4.3-3 AND 4.3-5 ARE BASED. (THE CORRESPONDING ANGLES INCLUDE A CORRECTION FOR ATMOSPHERIC REFRACTION)

AIR MASS	ANGLE
1.0	0
1.5	48°11'
2.0	60°
4.0	75°31'
6.0	80°42'
8.0	83°12'
10.0	84°48'

FIGURE 4.3-4. SOLAR GEOMETRY FOR PATH LENGTH CALCULATIONS

4.3.2.1.3 Lunar Radiation

It is apparent from Figure 4.3-1 that during the nights when the phase of the moon is greater than 60 degrees that lunar radiation dominates the target scene. Accompanying direct moonlight is also skylight in a manner similar to the relation that day skylight holds to the sun. Lunar radiation at the earth's surface is equally dependent as the sun upon atmospheric properties.

Lunar radiation is solar radiation reflected from the moon as modified by the reflectance characteristics of the moon. The term that is used to describe the ratio of reflected solar radiation to incident solar radiation from celestial bodies is called albedo. Figure 4.3-6 shows the lunar irradiance on a clear night for two air masses with a full moon. The spectral content of moonlight is shifted toward the red relative to solar radiation due to the moon's albedo (Figure 4.3-7).

The irradiance of the moon as a function of lunar phase or position relative to the sun can be determined by selecting the appropriate multiplier from Figure 4.3-8 and applying it to the full moon irradiance for the particular

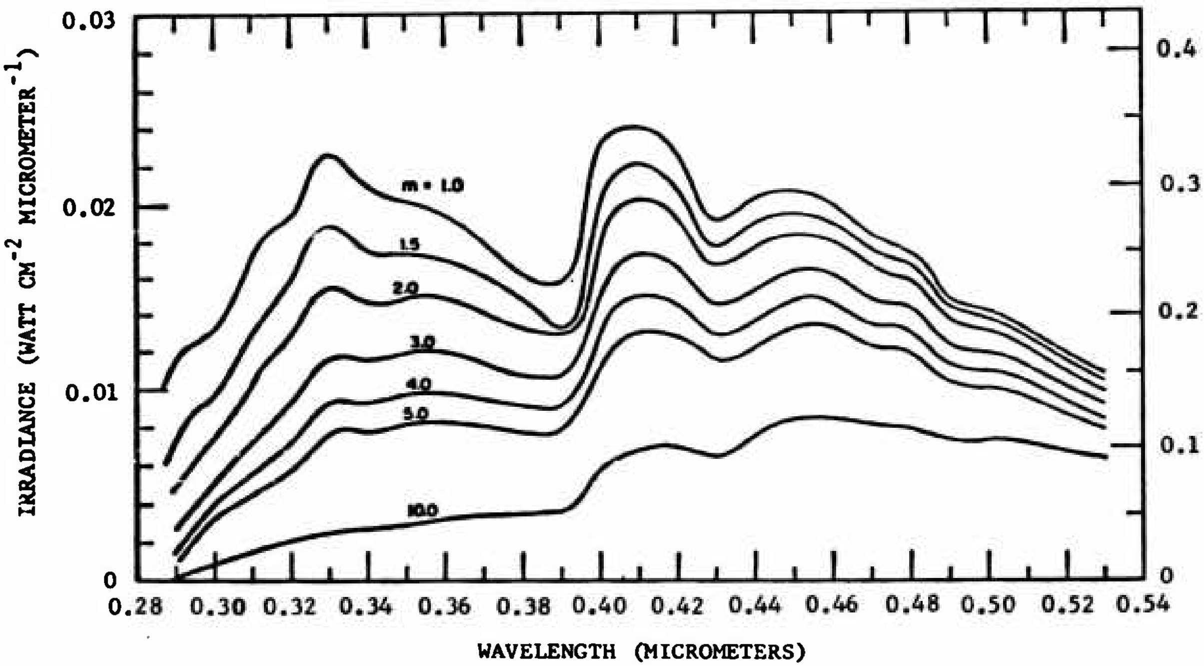


FIGURE 4.3-5. MONOCHROMATIC INTENSITY OF SKYLIGHT AS A FUNCTION OF WAVELENGTH, FOR A SKY IN WHICH RAYLEIGH SCATTERING TYPICALLY OCCURS, FOR SOLAR-RADIATION SLANT PATHS CORRESPONDING TO AIR MASS 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 AND 10.0 (82)

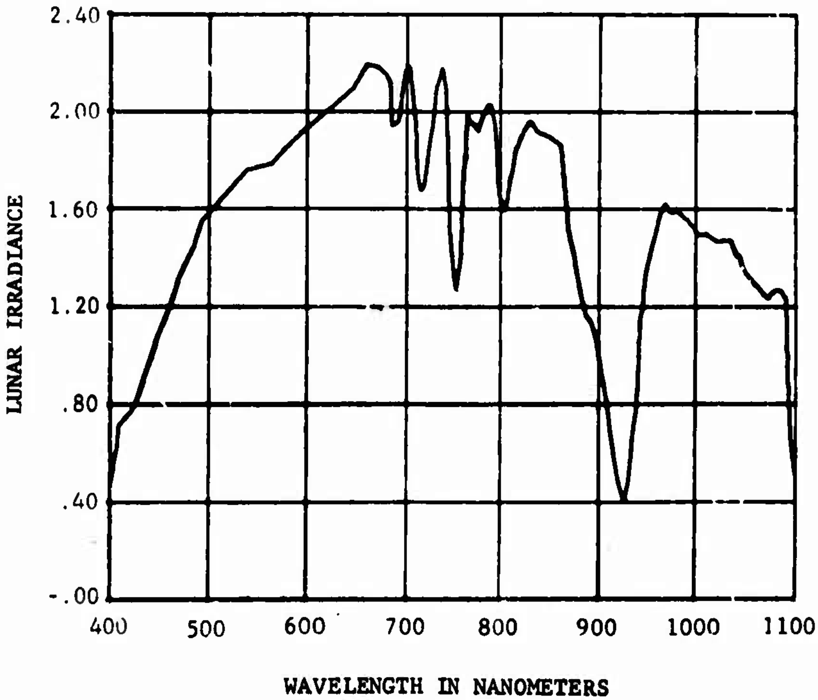


FIGURE 4.3-6. LUNAR IRRADIANCE FROM A FULL MOON THROUGH TWO AIR MASSES, MICRO-WATTS/NANOMETER/METER^2 (16)

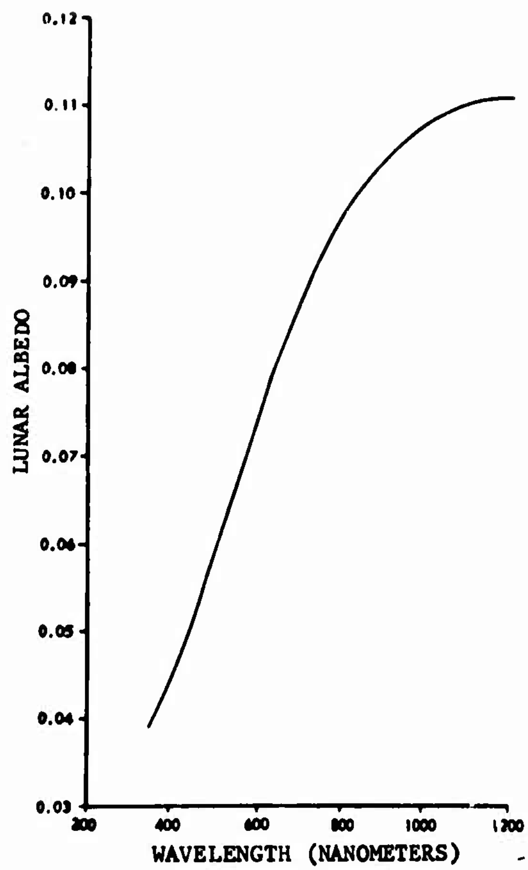


FIGURE 4.3-7. SPECTRAL ALBEDO OF THE MOON (16)

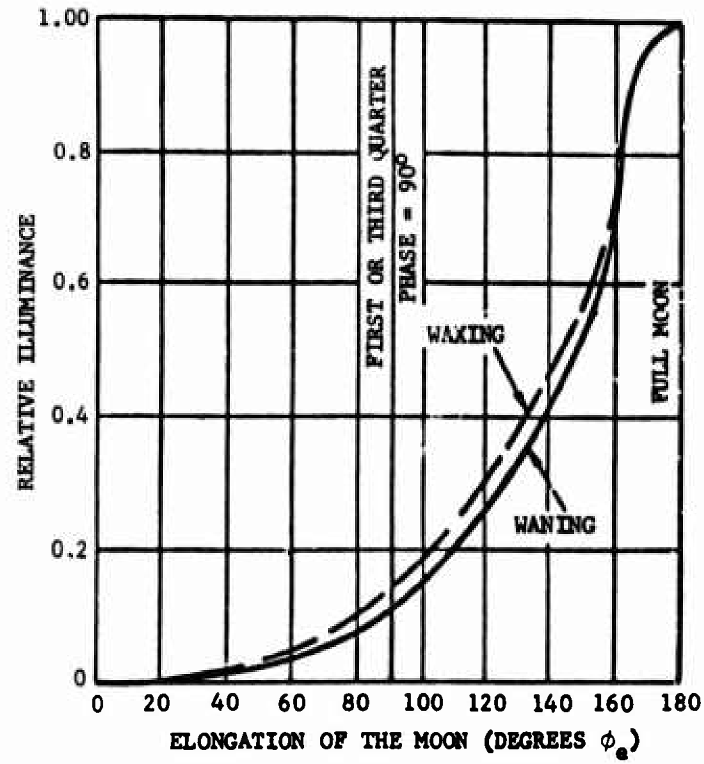


FIGURE 4.3-8. RELATIVE LUNAR ILLUMINANCE AS A FUNCTION OF ANGULAR DISTANCE ϕ_e FROM THE SUN (81)

atmosphere under consideration. The phase change of the moon is approximately 360 degrees/27.3 days = 13.2 degrees/day, so using the full moon as a reference the appropriate phase can be determined.

4.3.2.1.4 Starlight and Airglow

On moonless nights when scattered light from cities is negligible, the scene irradiance is determined by celestial radiation sources and airglow from the earth's atmosphere. The approximate makeup is:

Airglow	40 percent
Celestial	50 percent
Scattering from airglow and celestial radiation	10 percent

Airglow is primarily a line spectra resulting from emission from ionized atmospheric constituents. The sea level irradiances for the more intense lines are tabulated below.

TABLE 4.3-1. IRRADIANCE FROM AIRGLOW [16]

Wavelength (Micrometers)	Sea Level Irradiance (W/m^2)
0.48	1.01×10^{-8}
0.51	1.59×10^{-8}
0.55	4.00×10^{-8}
0.58	12.6×10^{-7}
0.63	2.10×10^{-7}
0.65	1.13×10^{-7}
0.68	5.66×10^{-7}
0.71	6.78×10^{-7}
0.73	3.57×10^{-7}
0.77	6.27×10^{-7}
0.83	1.59×10^{-6}
0.87	4.36×10^{-6}
0.93	3.57×10^{-6}
0.98	3.15×10^{-6}
1.03	1.09×10^{-5}
1.15	1.51×10^{-5}

Celestial radiation is the sum of the various radiating blackbodies in space. The total surface irradiance for a clear night is given in Figure 4.3-9. The data is averaged over 0.5 nanometer spectral intervals and normalized to a standard value of illumination.

4.3.2.1.5 Effects of Clouds

Cloud cover affects surface irradiance from natural sources for both night and day in approximately the same manner. From Biberman (16) the effect of a partly cloudy sky is to reduce surface irradiance by a factor of $\sqrt{10}$. For total overcast, irradiance is down a factor of 10.

4.3.2.2 Artificial Illumination

Artificial illumination is often used to provide sufficient light to enable the imaging system to overcome the problem of insufficient natural illumination. The illumination may be incidental to the imaging system, such as flares or battlefield searchlights, or be integral with the imaging system. Many low light level systems are subject to sensor damage from intense incidental light sources and care should be taken to avoid prolonged exposure to them.

Integral light sources include both continuous sources and pulsed sources. Continuous sources are less complex; but if located close to the image system, they become a strong source of backscattered light which can reduce the apparent target contrast. (A classic case of visibility reduction through backscattering is the case of driving an automobile at night in a fog with the automobile headlights on.) Pulsed sources are used with gated imaging systems where gating is used to reduce the backscatter effect (see Paragraph 4.3.3.4).

The irradiance at the earth's surface from the source is a function of the radiant power, geometric shape and spectral content of the beam in conjunction with the transmission characteristics of the atmosphere.

4.3.2.3 Conversion from Power to Photons

For low light level systems the fluctuation in photon arrival often is the limiting system noise factor (Paragraphs 3.4, 4.7.2.5, and 4.7.2.7). The signal to noise ratio inherent in this process is a function of the number of available photons. Some reference irradiance data (16) will be expressed in photon rates rather than units of power such as watts. Since the energy per photon is a function of wavelength, the conversion from power to photon rate is also spectrally dependent. The relation is

$$\dot{G}_\lambda = \frac{\Phi_\lambda \lambda}{hc} \qquad (4.3\text{-}1)$$

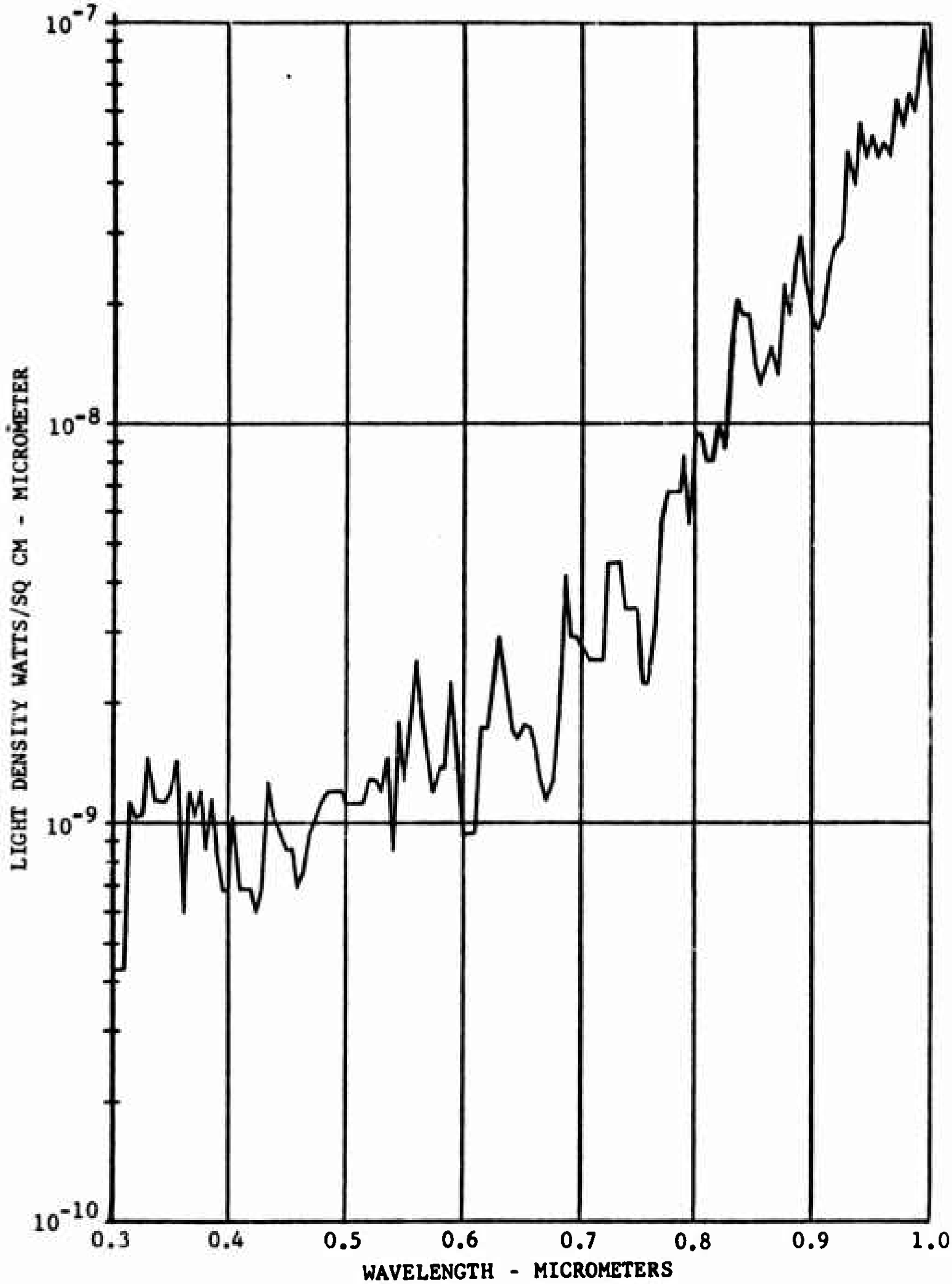


FIGURE 4.3-9. SPECTRAL DISTRIBUTION OF THE NIGHT SKY NORMALIZED TO 10^{-4} FOOT-CANDLES ILLUMINATION (35)

where

Φ is the flux in watts

$\dot{\bar{G}}_\lambda$ is the average photon rate in photons per second

λ is wavelength in centimeters

h is Planck's constant = 6.62×10^{-34} joules-second

c is 2.99×10^{10} centimeters/second

The total number of photons will depend upon the area in which the signal is to be defined and the integration time of the sensor. If t is the integration time, then the total number of photons on the average is

$$\bar{G}_\lambda = \frac{\Phi_\lambda \lambda t^*}{hc} \qquad (4.3\text{-}2)$$

and the signal to noise ratio per unit of spectral bandwidth is

$$S/N = \frac{G_{\lambda\,av}}{G_{\lambda\,rms}} = \frac{\bar{G}_\lambda^{**}}{\sqrt{\bar{G}_\lambda}} = \sqrt{\bar{G}_\lambda} = \sqrt{\frac{\Phi_\lambda \lambda t}{hc}} \qquad (4.3\text{-}3)$$

4.3.3 TARGETS AND BACKGROUNDS

4.3.3.1 General

The "signal" generated in an electro-optical imaging system arises from the differences in spectral radiance between various parts of the viewed scene. At any given wavelength, the signal is given by

$$i = k_s (\Delta L)_\lambda R_\lambda \qquad (4.3\text{-}4)$$

---

*To determine the total number of available photoelectrons in a detector (sensor), the number of photons must be integrated over the spectral response of sensor considering the quantum efficiency of the photo detector (see Paragraph 4.5.2.2). The number of photoelectrons, G, in an integration period is then

$$G = \frac{t}{hc} \int_{\lambda_1}^{\lambda_2} \eta_\lambda \Phi_\lambda \lambda \, d\lambda$$

**This relationship results from the statistics of the photon distribution time.

where

i is the signal generated in the E-O sensor, due to contributions at the wavelength λ

k_s is a proportionality factor dependent upon system design

$(\Delta L)_\lambda$ is the apparent difference in spectral radiance* between neighboring scene elements

R_λ is the relative spectral response of the sensor (including optical filters).

The total signal generated in the sensor is given by

$$i = k_s \int_{\lambda=0}^{\infty} (\Delta L)_\lambda R_\lambda \, d\lambda \qquad (4.3\text{-}5)$$

Note that in the definition of $(\Delta L)_\lambda$, the adjective apparent was used. This is to account for any change in radiance differences which might occur due to the atmosphere between the scene and the sensor.

Most of the time scenes are not thought of in terms of their spectral radiances, but in more familiar terms related to the spectral region of interest. Therefore, the signal generated is usually expressed in special terms which have become historically wedded to the sensor.

4.3.3.2 TV Spectrum

Television and direct view image intensifier systems generally work in the visible and near infrared spectrum. They depend for their signals upon differences in spectral reflectivities between various parts of the viewed scene. The radiance of an ideal diffuse, or Lambertian, reflector is related to irradiance by

$$L_\lambda = \frac{E_\lambda \rho_\lambda}{\pi} \qquad (4.3\text{-}6)$$

where

L_λ is the radiance or luminance of the diffusely reflecting object

---

*Radiance is the flux per unit area per unit solid angle (see Appendix A).

E_λ is the irradiance or illuminance falling upon the object

ρ_λ is the reflectance of the object.

When using Lambert-based units, such as foot-lamberts, the π is omitted from Equation (4.3-6) (see Appendix A). This is supposed to be a convenience, eliminating the factor π from calculations.

In many calculations, it is assumed that the reflecting surfaces of the scene are ideally diffuse, or Lambertian. That is, the radiance or luminance is constant in all directions of view. This is seldom the case. The reflectance of most substances is a function of the incident angle of illumination, as well as the direction of view. The directional reflectance characteristics of man-made and natural objects tend to differ, so that contrast is generally a strong function of viewing angle and sun or moon position. Whenever directional reflectance data is available, it should be used. When it is not available, the diffuse reflectance assumption may be used in first analyses. Substituting Equation (4.3-6) into Equation (4.3-4),

$$i = k_s \frac{E_\lambda}{\pi} (\Delta\rho)_\lambda R_\lambda \tag{4.3-7}$$

where $(\Delta\rho)$ is the difference in spectral reflectance between neighboring scene elements.

Since television systems first operated primarily in the visual spectrum, performance analyses were related to the extensive "visibility" literature which concerned itself with the performance of the human eye. One concept which is carried over from "visibility" is that of contrast. The following is an excerpt from the paper, "Visibility", by S. Q. Duntley, et al (Reference (87), page 544):

"Throughout the literature of visibility, the ratio of the radiances (or luminance) of any object decoupled from its background to the radiance (or luminance) of its background in the direction of observation, or some function of that ratio, has been referred to as contrast. In this article, the ratio just defined will be denoted by R and referred to as <u>ratio contrast</u>. Since any function of R also represents a form of contrast, there are, obviously, a limitless number of possible forms, each of which could be named.

Most of the literature of visibility, both psycho-physiological and physical, has made exclusive use of the contrast function R-1, because it provides important advantages in both disciplines. Fundamentally, the generalization, geometrically identical

objects are equally detectable if their universal contrasts are equal in magnitude even if opposite in sign, which refers to R-1 or its algebraic equivalent $\Delta L/L$, states that flux increments (ΔL) are as detectable as flux decrements ($-\Delta L$). Since negative contrast ($-\Delta L/L$) can never exceed 1 in absolute value, whereas the magnitude of positive contrast is limitless, objects lighter than their backgrounds can be vastly more detectable than otherwise identical objects darker than their backgrounds."

Duntley defines the function, R-1, as universal contrast. (See Eq. (4.3-8) for definition of R).

It is the practice, in television usage, to define contrast as the difference between scene highlight and lowlight luminances, divided by scene highlight luminance. This, in effect, restricts contrast to values between zero and unity. For targets which are darker than their background, television contrast is defined as 1-R, or just the negative of universal contrast. For targets which are brighter than their background, television contrast becomes (R-1)/R, which is universal contrast divided by the ratio of target to background luminance. This form of contrast definition is well suited to television systems, which have an intrascene dynamic range capability far less than that of the human eye.

The use of modulation transfer functions in the analysis of electro-optical imaging systems leads to yet one more form, called modulation contrast, which is the difference between highlight and lowlight luminances, divided by the sum of highlight and lowlight luminances. This form of contrast is especially useful for analysis of system response to bar patterns. The relationship to ratio contrast is $\pm(R-1)/(R+1)$, the positive value applying when the target is brighter than the background.

The three forms of signal contrast and their relationship to ratio contrast are summarized in Table 4.3-2. The ratio contrast, R, is defined by

$$R = \frac{L_T}{L_B} = \frac{\rho_T}{\rho_B} \qquad (4.3\text{-}8)$$

where

L_T is target radiance or luminance

L_B is background radiance or luminance

ρ_T is target reflectance

ρ_B is background reflectance.

TABLE 4.3-2. CONTRAST RELATIONSHIPS

Form of Contrast	Relationship to Ratio Contrast, R		
Universal	$C_U = R-1 = \frac{L_T-L_B}{L_B}$	$0 < R < \infty$	(4.3.9)
Television	$C_T = 1-R = \frac{L_B-L_T}{L_B}$	$R < 1$	(4.3.10)
	$C_T = \frac{R-1}{R} = \frac{L_T-L_B}{L_T}$	$R > 1$	
Modulation	$m = \frac{1-R}{1+R} = \frac{L_B-L_T}{L_B+L_T}$	$R < 1$	(4.3.11)
	$m = \frac{R-1}{R+1} = \frac{L_T-L_B}{L_B+L_T}$	$R > 1$	
	Relationship to Modulation, m		
Universal	$C_U = \frac{-2m}{1+m}$	$R < 1$	(4.3.12)
	$C_U = \frac{2m}{1-m}$	$R > 1$	
Television	$C_T = \frac{2m}{1+m}$	$0 < R < \infty$	(4.3.13)

The various types of signal contrast are plotted as a function of ratio contrast, in Figure 4.3-10. For targets which are darker than their backgrounds, the various forms do not yield significantly different values, although at low contrast values modulation contrast yields only half the values of universal or television contrast. For targets brighter than their backgrounds, the values of universal contrast quickly diverge from the other two forms. It should be recognized that the limited dynamic

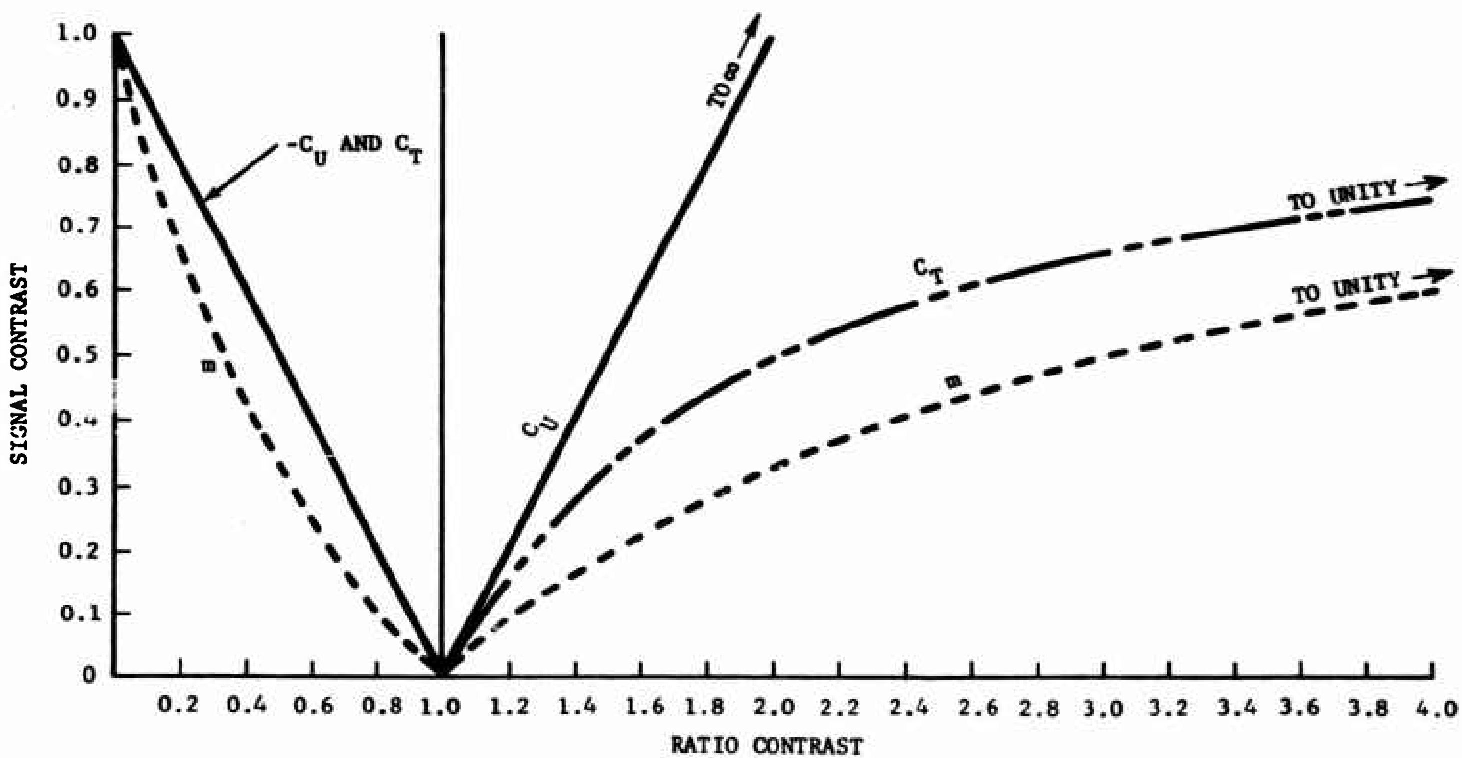


FIGURE 4.3-10. RELATIONSHIP OF VARIOUS FORMS OF CONTRAST

range of most E-O sensors, particularly LLLTV systems, constrains the actual contrast which can be handled in a linear fashion, so that linear analyses may not always apply. Middleton (Reference (31), page 61) points out that "very large (but not in practice infinite) values of C_U arise when we consider lights at night. In the daytime, contrasts (C_U) greater than about 10 seldom occur."

The advantage of using contrast is that it always involves the ratio of radiances or luminances, and therefore the ratio of scene reflectances can just as well be used, so that contrasts can be computed as a function of inherent target and background properties, independent of the absolute value of scene irradiance or illuminance.

Specific detailed examples of directional reflectivity are given in Part III of Reference (87). No spectral data are included in that reference, however. Compendiums of reflective data are given in Reference (90, Chapter 7, (84), Chapters 4 and 5, and (91). This last reference also computes the signals generated when various targets in certain backgrounds are viewed by typical low light level sensors, with varying illumination conditions. The work is most useful in quickly comparing sensor performance. Comprehensive compilations of reflectance data are being published by the Target Signature Analysis Center at the University of Michigan (see, for example, Reference (92)). Reflectance data in Reference (87) are effective visual reflectance, that in (90) covers the visual spectrum, (84) covers the IR from 1 to 15 μm, while (91) covers the visible and near IR spectrum. Both visible and IR data are included in (92).

Some typical luminous reflectance values are given in Table 4.3-3 (119). The spectral reflectances of these objects are given in Figure 4.3-11 (119). Note the high reflectance values exhibited in the near IR by vegatative formations.

Contrast can also arise due to the different values of illumination falling on vertical and horizontal surfaces (Reference 88)) and shadowing effects. Thus, sand dunes can provide sharp contrasts at certain viewing angles.

Incandescent sources in the field of view can be a hindrance or a help to low light level imaging systems. They can cause "blooming" on the display, so that some detail is veiled. On the other hand, even a dim lamp can be spotted at very long ranges at night with a low light level viewing device.

4.3.3.3 FLIR Spectrum

While in the visible and near-infrared spectral regions radiance or luminance differences arise due to differences in reflectance, self-emission becomes predominant in those wavelength regions usually used by FLIR (the 3 to 5 μm and 8 to 14 μm atmospheric windows). In this case, differences in emissivity or temperature between various parts of the viewed scene are the origin of the "signal" for a FLIR set.

TABLE 4.3-3. LUMINOUS REFLECTANCE OF VARIOUS NATURAL OBJECTS IN PERCENT 119

		Smithsonian Tables	Sewing Handbook	Krinov	Schimpf, Aschenbrenner
Class A	Water Surfaces				
1	Bay	3-4			
2	Bay and river	6-10			
3	Inland water	5-10		5	
4	Ocean	3-7			
5	Ocean, deep	3-5			
Class B	Bare Area and Soils				
1a	Snow, fresh fallen	70-86		77	
1b	Snow, covered with ice			75	
2	Limestone, clay			63	
3	Calcareous rocks		30		
4	Granite		12		
5	Mountain tops, bare			24	
6a	Sand, dry		31	24	
6b	Sand, wet		18		
7a	Clay soil, dry		15		
7b	Clay soil, wet		7.5	9	
8a	Ground, bare, rich soil, dry	10-20	7.2	9	
8b	Ground, bare, rich soil, wet		5.5		
8c	Ground, black earth, sand loam			3	
8d	Field, plowed, dry	20-25			
Class C	Vegetative Formations				
1a	Coniferous forest, winter			3	
1b	Coniferous forest, summer	3-10		8	
1c	Deciduous forest, summer			10	
1d	Deciduous forest, fall			15	
1e	Dark hedges		1		
2	Coniferous forest, summer, from airplane			3	2
3a	Meadow, dry, grass	3-6		8	
3b	Grass, lush	15-25		10	
4	Meadow, low grass, from airplane			8	7
5	Field crops, ripe	7		15	
Class D	Roads and Buildings				
1	Earth roads			3	
2	Black top roads		8	9	
3a	Concrete road, smooth, dry		35		
3b	Concrete road, smooth, wet		15		
4a	Concrete road, rough, dry		35		
4b	Concrete road, rough, wet		25		
5	Buildings			9	
6	Limestone tiles		25		

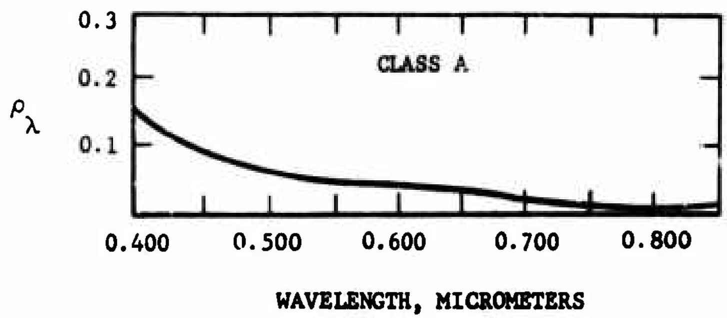
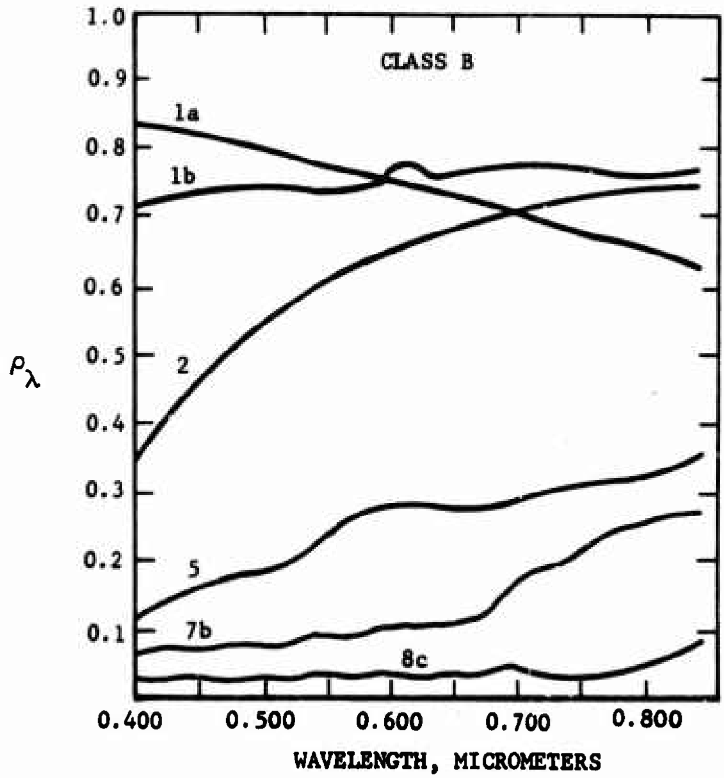
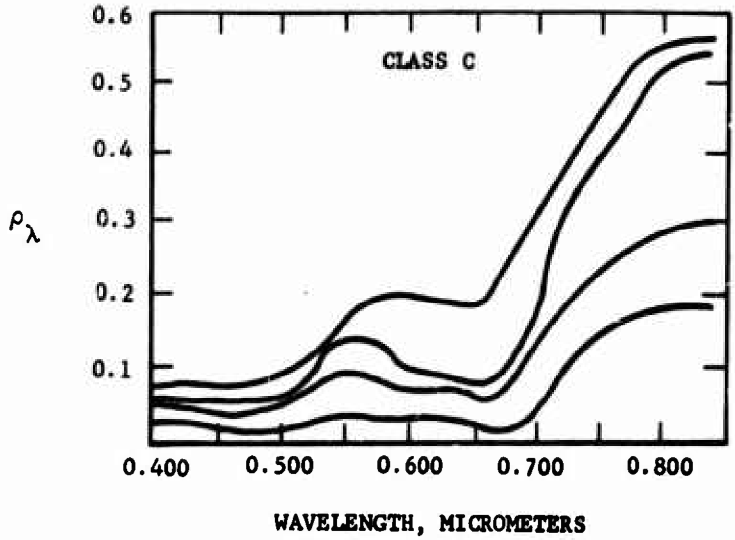


FIGURE 4.3-11. SPECTRAL REFLECTANCE FOR ELEVEN TYPES OF NATURAL OBJECTS [119]



CLASS B
1a
1b
2
5
7b
8c
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
ρ_λ
0.400
0.500
0.600
0.700
0.800
WAVELENGTH, MICROMETERS



CLASS C
0.6
0.5
0.4
0.3
0.2
0.1
ρ_λ
0.400
0.500
0.600
0.700
0.800
WAVELENGTH, MICROMETERS

Figure 4.3-12 (84) plots the spectral radiance of some objects measured in the daytime. The radiance at wavelengths shorter than about 3 μm is due to reflected solar radiation, while that above 3 μm is due to self emission. Figure 4.3-13 shows the spectral radiance of the same objects, measured at night. In this case, the radiance at wavelengths less than 3 μm is nearly negligible.

Figure 4.3-14 is a plot of the spectral reflectance of some surfaces covering the wavelength region from the visible through the usual FLIR bands. For an opaque surface at a certain temperature, spectral emissivity is the complement of spectral reflectance, i.e., emissivity plus reflectance equals unity at any given wavelength.

In the case where the scene (is assumed to be) at a uniform temperature and the signal is due to emissivity differences.

$$i_\lambda = k_s (\Delta L)_\lambda R_\lambda = k_s (\Delta \epsilon)_\lambda L_\lambda R_\lambda \qquad (4.3\text{-}14)$$

where

$(\Delta\epsilon)_\lambda$ is the difference in spectral emissivity between neighboring elements

L_λ is the average scene spectral radiance.

Where the signal is assumed to be due to temperature differences

$$i_\lambda = k_s (\Delta L)_\lambda R_\lambda = k_s (\Delta T) \epsilon_\lambda \frac{\partial L_\lambda}{\partial T} R_\lambda \qquad (4.3\text{-}15)$$

where

ΔT is the temperature difference between neighboring scene elements

ϵ_λ is scene spectral emittance

$\frac{\partial L_\lambda}{\partial T}$ is the change in scene spectral radiance with a change in temperature.

The quantity $\partial L_\lambda/\partial T$ can be found by using Equation (42) and Table III of the blackbody tables by Pivovonsky and Nagel (Reference (89)) for example.

The spectral radiance of a Lambertian blackbody is given by Planck's law

$$L_\lambda = \frac{2c^2 h}{\lambda^5 \left[\exp (hc/\lambda k_B T) - 1\right]} \quad W\ cm^{-2}\ sr^{-1}\ cm^{-1} \qquad (4.3\text{-}16)$$

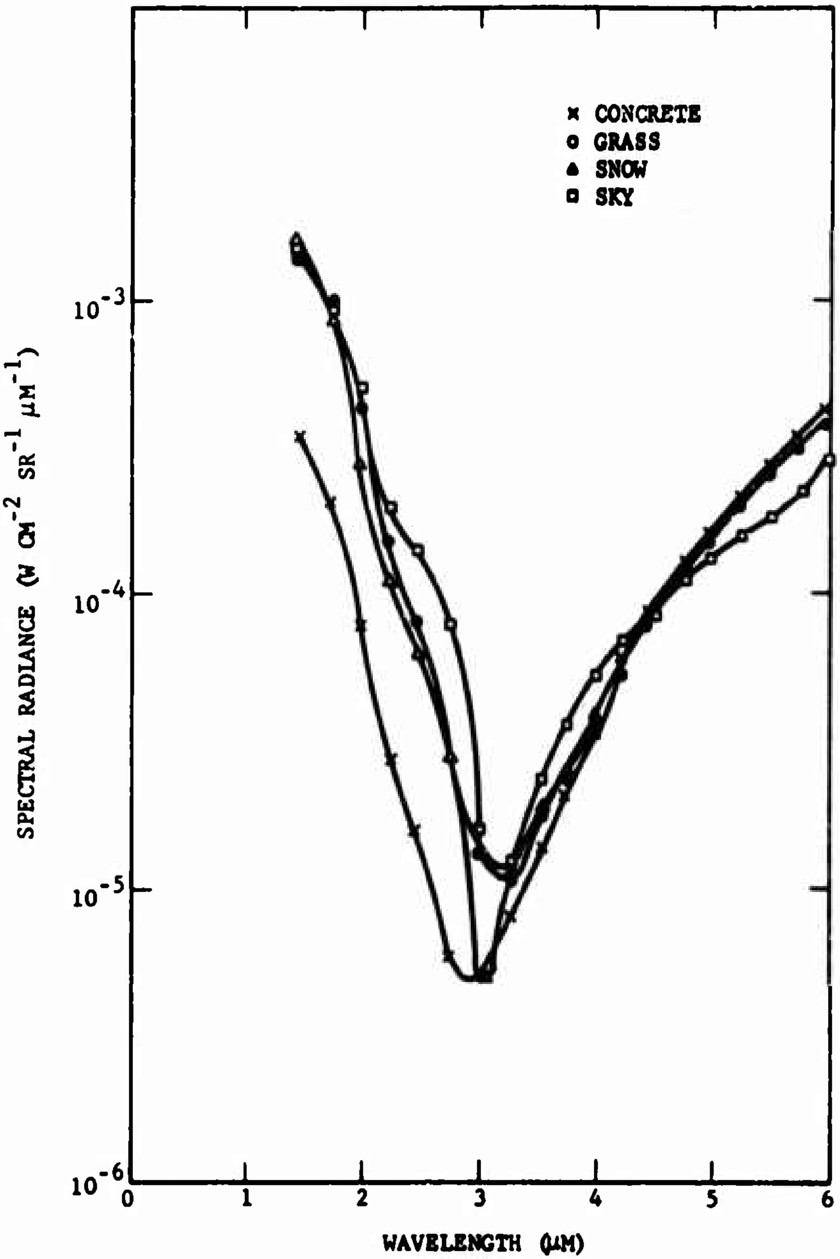


FIGURE 4.3-12. SPECTRAL RADIANCE OF SKY, CONCRETE, SNOW, AND GRASS, WINTER DAY [84]

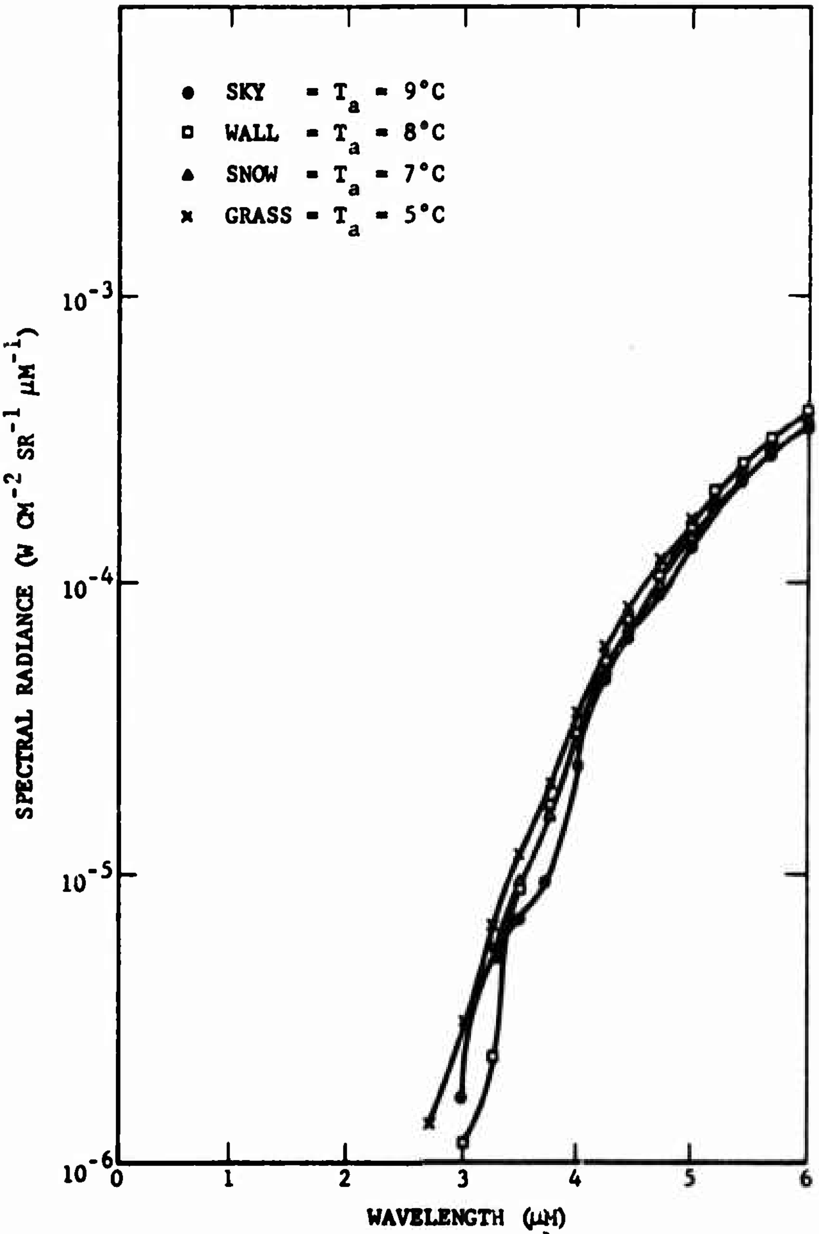


FIGURE 4.3-13. SPECTRAL RADIANCE OF SKY, CONCRETE, SNOW, AND GRASS, WINTER NIGHT [84]

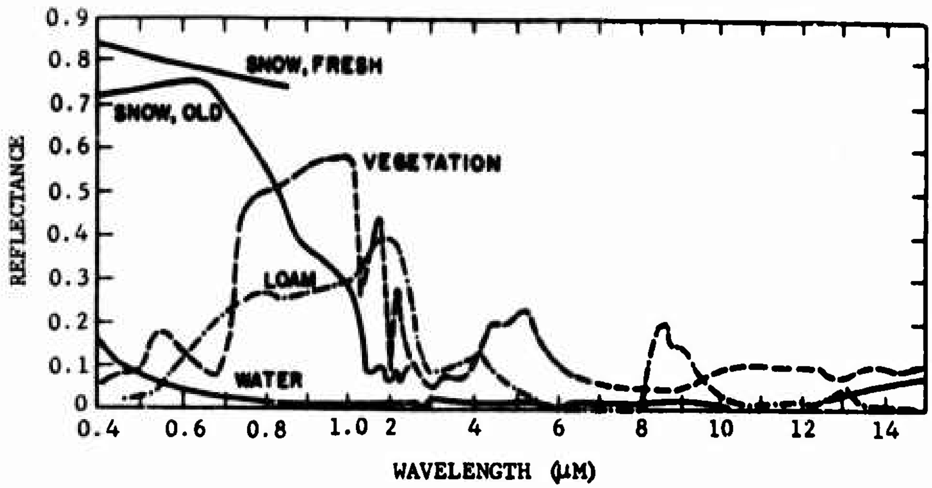


FIGURE 4.3-14. TYPICAL REFLECTANCE OF WATER SURFACE, SNOW, DRY SOIL AND VEGETATION [59]

where

c is the speed of light, 3×10^{10} cm/sec

h is Planck's constant, 6.65×10^{-34} W $\sec^2$

λ is wavelength, cm,

k_B is Boltzmann's constant, 1.38×10^{-23} W sec K^{-1}

T is temperature in degrees Kelvin, K.

To find the spectral radiance of a Lambertian greybody or a selective radiator (see Paragraph 3.1) the above expression is multipled by ϵ_λ, the spectral emissivity.

Figure 4.3-15 (86) is a plot comparing the spectral radiance of some terrain features to that of a blackbody.

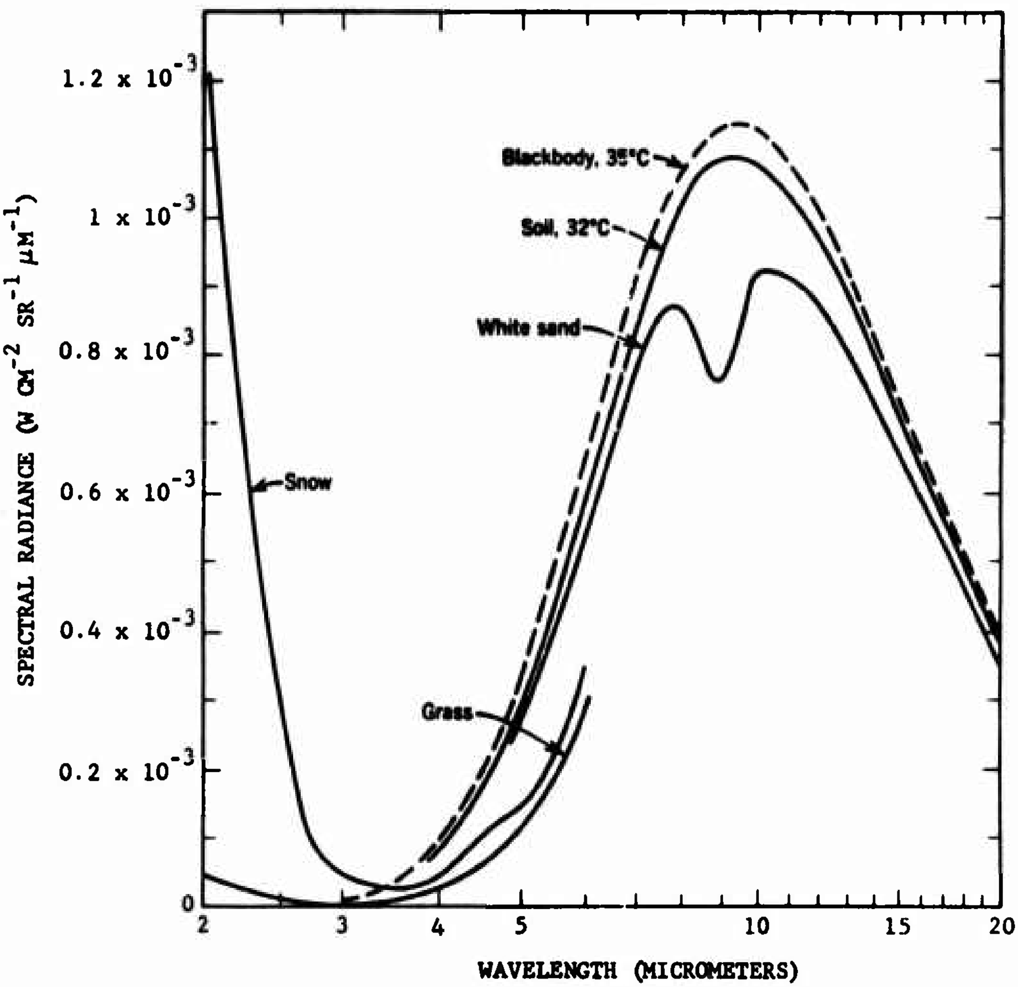


FIGURE 4.3-15. SPECTRAL RADIANCE OF TYPICAL TERRAIN MATERIALS AS OBSERVED DURING THE DAYTIME [86]

The total radiance of a Lambertian blackbody is given by the Stefan-Boltzmann law,

$$L = \frac{\sigma_B T^4}{\pi} \quad \text{W cm}^{-2}\ \text{sr}^{-1} \tag{4.3-17}$$

where

σ_B is the Stefan-Boltzmann constant, 5.67×10^{-12} W cm^{-2} K^{-4},

T is temperature in Kelvins, K.

On the assumption that a constant or average emissivity can be found, the total radiance of a graybody is given by

$$L = \frac{\epsilon \sigma_B T^4}{\pi} \quad \text{W cm}^{-2}\ \text{sr}^{-1} \tag{4.3-18}$$

This expression is sometimes differentiated to yield the quantity $\partial L/\partial T$,

$$\frac{\partial L}{\partial T} = \frac{4\epsilon\, \sigma_B T^3}{\pi} \tag{4.3-19}$$

This procedure can lead to erroneous results, for most sensors use only a small portion of the total spectrum. Therefore, it is preferable to determine the value of $\partial L/\partial T(\lambda)$ from measured or tabulated data (89), and then integrate these values over the appropriate wavelength region.

The wavelength of peak spectral radiance for a blackbody is given by the Wein Displacement law,

$$\lambda_{max} T = \text{constant} = 2897.9 \text{ micrometer-Kelvin}$$

where

λ_{max} is the wavelength of peak spectral radiance, μm,

T is the temperature in Kelvin, K.

Thus the earth, which is at a temperature near 300 K, has its peak radiance at about 10 μm. The sun, which has a blackbody temperature near 5800 K, has its peak radiance at about 0.5 μm.

A quantitative concept of contrast, as defined in Paragraph 4.3.3.2, is not usually employed in FLIR sensor evaluation. This is perhaps because any such contrast values so computed would be very small, since the signals used in FLIR imagery result from very small temperature (radiance) differences superimposed on a substantial background temperature (radiance).

4.3.3.4 Atmospheric Effects

In Paragraph 4.3.3.1 in the definition of the signal function, the term "apparent" radiance difference was used. When looking at a distant object with the unaided eye, the "apparent" radiance of the object is different from the "inherent" radiance of the object. Here the apparent radiance is that radiance the object appears to have seen at a distance R through the atmosphere, as opposed to the inherent radiance it has when viewed up close. The apparent radiance, L_R is

$$L_R = L_o \tau_a + L_P \tag{4.3-20}$$

where

L_o is inherent radiance of the object

τ_a is the atmospheric transmittance of the path of sight

L_P is the radiance of the path of sign.

The first term of the above equation accounts for radiation which originates at the target and should reach the observer but is lost due to atmospheric attenuation. The second term accounts for radiation which is scattered into the eyes of the observer by the air in the path, and appears to originate at the object. Thus a black object which has zero inherent luminance appears lighter and lighter as it is viewed from a great distance. Brighter objects appear darker and darker as they are viewed from a greater distance. Finally, all objects assume the luminance of the horizon sky as they are viewed beyond the range of visibility.

Bailey and Mundie have evaluated the effect of atmosphere upon the performance of various sensors (Reference (93)). In the visual and near IR spectrum, where adequate light is available, the performance of the human eye is dependent almost solely on universal contrast. It is generally assumed that in an EO imaging system which performs linearly, contrast is the important determinant of system performance. Thus the concepts of contrast transmittance as employed in visibility calculations are applicable.

It can be shown (see Equation 6.3 of Reference (87) and Equation 4.21 of Reference (31) that the atmospheric transmittance of universal contrast is

$$\frac{C_R}{C_o} = \frac{L_o \, \tau_a}{L_R} \tag{4.3-21}$$

where

C_R/C_o is atmospheric contrast transmittance

C_R is apparent universal contrast at range R

C_o is inherent universal contrast

L_o is inherent background radiance

τ_a is atmospheric transmittance of the path of signt

L_R is apparent background radiance at the range r (see Equation 4.3-20).

For a specific atmospheric condition, examples of the use of Equation (4.3-21) and equivalent forms are given on pages 570 ff of Reference (87).

In general, Equation (4.3-21) may not be convenient to use because of lack of path radiance data necessary to calculate the apparent background radiance. Duntley (5) gives another form of contrast transmittance equation, which Bailey and Mundie (93) have put in the form,

$$\frac{C_R}{C_o} = \frac{1}{1 + H\left[\dfrac{1 - \tau_a}{\tau_a}\right]} \tag{4.3-22}$$

where H is a ratio discussed below.

When the object is viewed along a horizontal path, H is the ratio of the horizon sky radiance to the inherent background radiance, L_H/L_o. The horizon sky radiance must be measured in the direction of the object. For the special case of an object viewed against the horizon sky, H is unity and Equation (4.3-22) reduces to τ_a, the atmospheric path transmittance. When H is greater than unity, i.e., when an object is viewed against a dark background, contrast attenuation is worse than τ_a at any given range. Conversely, when H is less than unity, contrast attenuation is not so severe as τ_a. Figure 4.3-16, taken from Middleton (31), plots contrast transmittance, for several values of H, as a function of r/V_2, where r is the range to the target and V_2 is the meteorological range, which will be defined in Eq. (4.3-24).

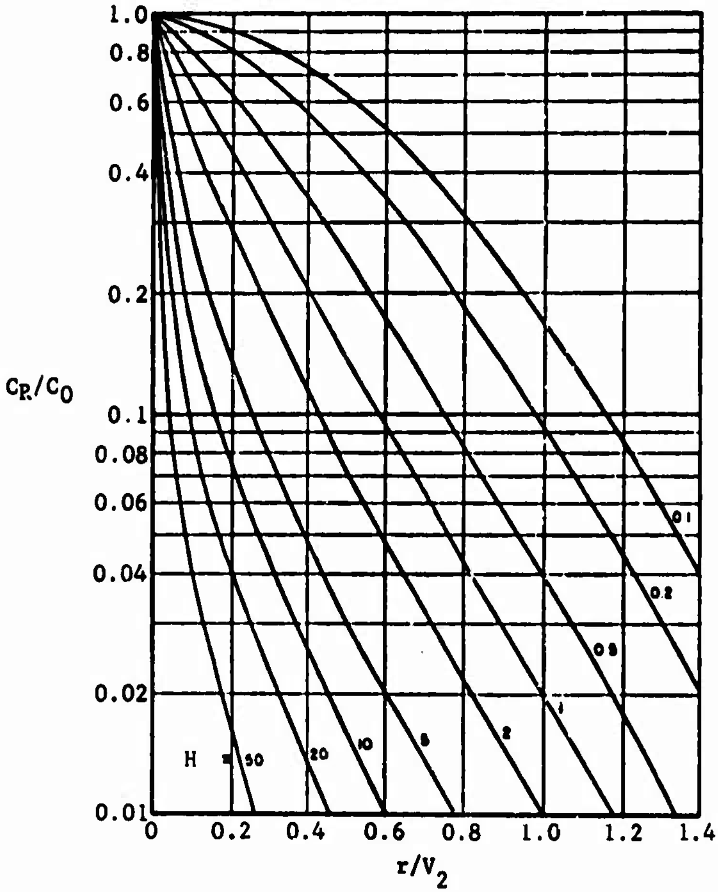


FIGURE 4.3-16. CONTRAST TRANSMITTANCE AS A FUNCTION OF RANGE (31)

When the path of sight is from an aircraft to the ground, the symbol H represents the "sky-ground ratio." Table 4.3-4 lists values of the sky-ground ratio, as reported by Duntley (5).

TABLE 4.3-4. SKY-GROUND RATIOS

Sky Condition	Ground Condition	Sky-Ground Ratio
Overcast	Fresh snow	1
Overcast	Desert	7
Overcast	Forest	25
Clear	Fresh snow	0.2
Clear	Desert	1.4
Clear	Forest	5

Where light levels are lower, such that signal to noise ratio becomes an important consideration, Bailey and Mundie (93) point out that it is not contrast transmittance which is important, but the "transmittance" of signal-to-photon noise ratio. This applies equally well to the human eye and to photoelectron shot noise limited EO sensors. The "transmittance" of signal-to-photon-noise ratio is given by the relationship (93)

$$\tau_{ph} = \frac{|L_{T,R} - L_{B,R}|}{\sqrt{L_{T,R} + L_{B,R}}} = \sqrt{\tau_a}\sqrt{\frac{C_R}{C_o}} \qquad (4.3\text{-}23)$$

where

τ_{ph} is the atmospheric "transmittance" of signal-to-photon-noise ratio

$L_{T,R}$ is the apparent radiance of the target

$L_{B,R}$ is the apparent radiance of the background

τ_a is atmospheric beam transmittance

C_R/C_o is atmospheric contrast transmittance, given by Equation (4.3-21) or (4.3-22).

The transmittance, τ_{ph}, is the geometric mean of the atmospheric beam transmittance and atmospheric contrast transmittance.

The calculation of signal to noise ratio transmittance for a system which uses a pulsed active illuminator is simpler than the preceding two cases, if perfect "gating" is assumed. When a sensor is gated, it is rendered insensitive to radiation except for the brief interval that the reflected illuminator pulse arrives at the sensor. Therefore, the path radiance need not be considered, at least in the ideal case. The signal (arising from the difference in target and background reflectances) is proportional to τ_a^2, since the illuminator power travels two ways. For a photoelectron shot noise limited system, the noise will then be proportional to $\sqrt{\tau_a^2}$, so that the transmittance of signal-to-noise ratio is just equal to τ_a. The subject of active illumination is treated in more depth in Chapter 17 of (99).

In the FLIR operating regions, signal to noise ratio is also usually important. In this case, however, the noise is primarily photon or photoelectron shot noise due to the very substantial background. Bailey and Mundie show that it is simply the beam transmittance which is important in the FLIR region, so that the transmittance of signal to noise ratio is just equal to beam transmittance for viewing paths which terminate on the earth.

A plot of spectral transmittance of the atmosphere was given in Figure 3.1-6, showing the useful atmospheric "windows". For specific transmittance calculations, an atmospheric model must be employed.

Several models of atmospheric transmittance are used. For the visible and near IR regions, the model of (94) of Chapter 7 of (90) is commonly used. This model is usually defined as the clear standard atmosphere, and has a sea level path meteorological range (V_2) of about 25 km at the peak photopic wavelength of 0.55 μm. Meteorological range is defined as that range at which the beam transmittance is 2 percent. For a homogeneous atmosphere,

$$\tau_a = \exp - \sigma_a r \tag{4.3-24}$$

where

τ_a is atmospheric beam transmittance

σ_a is attenuation coefficient, km^{-1}

r is range, km.

The meteorological range is found by

$$\tau_a = 0.02 = \exp -3.912 = \exp -\sigma_a V_2 \tag{4.3-25}$$

where V_2 is meteorological range.

From this,

$$V_2 = \frac{3.912}{\sigma_a} \qquad (4.3.26)$$

For days which are not so clear as the standard clear day, σ_a will be greater and V_2 correspondingly less. Figure 4.3-17 shows the relationship between σ_a and meteorological range. It also shows weather conditions as defined on the international visibility scale (Reference (95)). Figure 4.3-18 shows the spectral dependence of the atmospheric extinction (attenuation) coefficient for several atmospheric conditions (Reference (118)). Attenuation coefficients for the standard clear day are given as a function of altitude and wavelength in (94). Attenuation coefficients for hazy days are given in (120).

Atmospheric transmittance in the FLIR spectra are not directly inferred from that in the visible spectrum. Except in extreme cases of fog, the primary attenuation mechanism in the visible is scattering due to the atmospheric aerosol. Transmittance at FLIR wavelengths is more a function of the molecular absorption. Wator vapor is the most important and most variable absorber in the FLIR spectral windows. Atmospheric models which have been popular for FLIR calculations are those of (96) and (97). Recently, a more complete model has been published (59). This document outlines nomographic methods for calculating atmospheric transmittance for the spectrum 0.25 μm to 15 μm. Figures 4.3-19 and 4.3-20 are examples of calculations made from Reference (59) for the 8 to 14 μm spectrum.

In the design of high resolution imaging systems, the effect of atmospheric turbulence upon MTF (see Paragraph 3.3) should also be considered. "Turbulence in the atmosphere between a point object and an optical imaging system causes the image of that point to be degraded in several ways. The image will fluctuate randomly in both intensity and position, and at any instant in time will generally have a larger and/or more irregular blur circle than that corresponding to the imaging system without turbulence." (Reference 98)

The effects of atmospheric turbulence are often neglected in system analyses, most likely because of the paucity of quantitative data which can be readily applied to an imaging problem. Figure 4.3-21 plots MTF due to atmospheric turbulence in an 11 km horizontal path, based upon a few measurements (121). These measured data were later correlated with theory, with good agreement (122).

The MTF due to atmospheric turbulence is given by (123)

$$\tilde{r}_{ATM} = \exp -D/2 \qquad (4.3\text{-}27)$$

where D is the "wave structure function" of the path of sight.

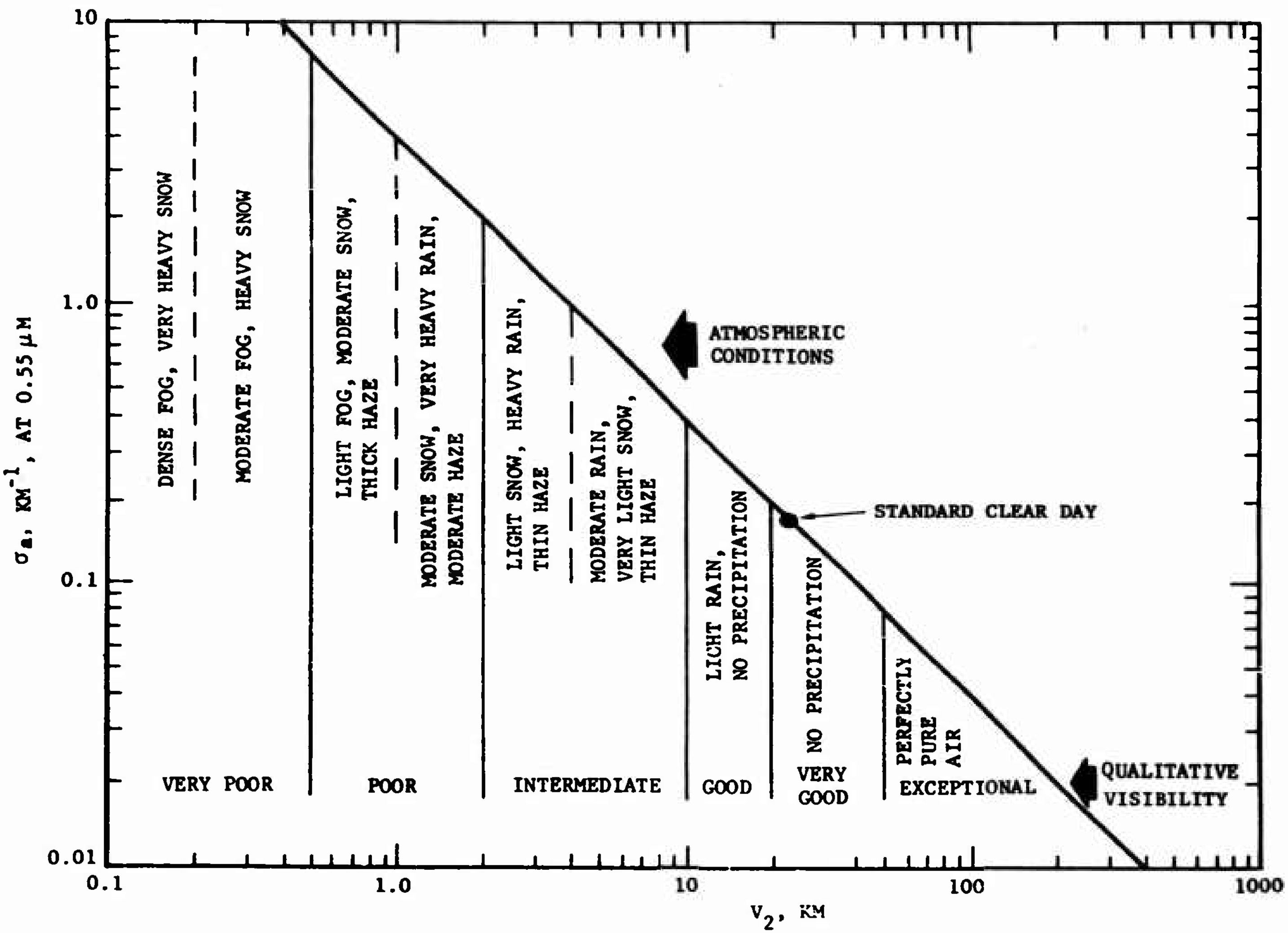


FIGURE 4.3-17. ATMOSPHERIC ATTENUATION COEFFICIENT AS A FUNCTION OF VISIBILITY (95)

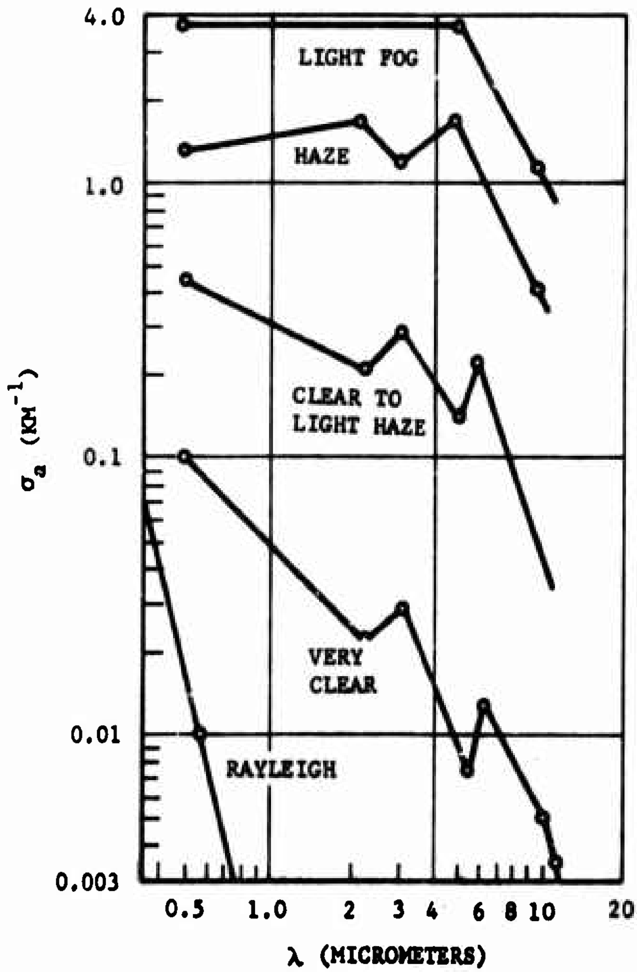


FIGURE 4.3-18. TYPICAL VALUES OF ATMOSPHERIC EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH (118)

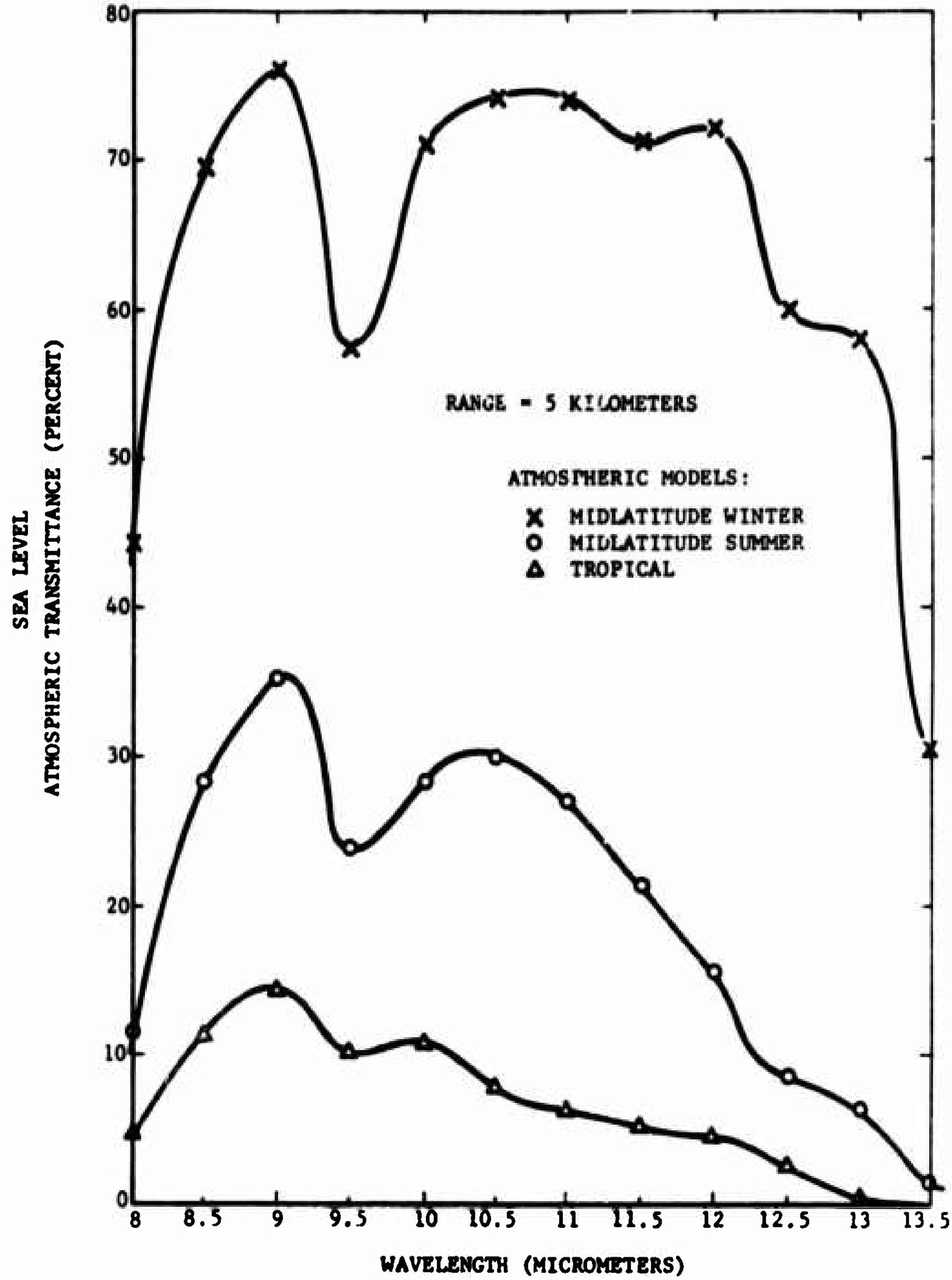


FIGURE 4.3-19. SEA LEVEL SPECTRAL TRANSMITTANCE IN 8 TO 14 μM WINDOW

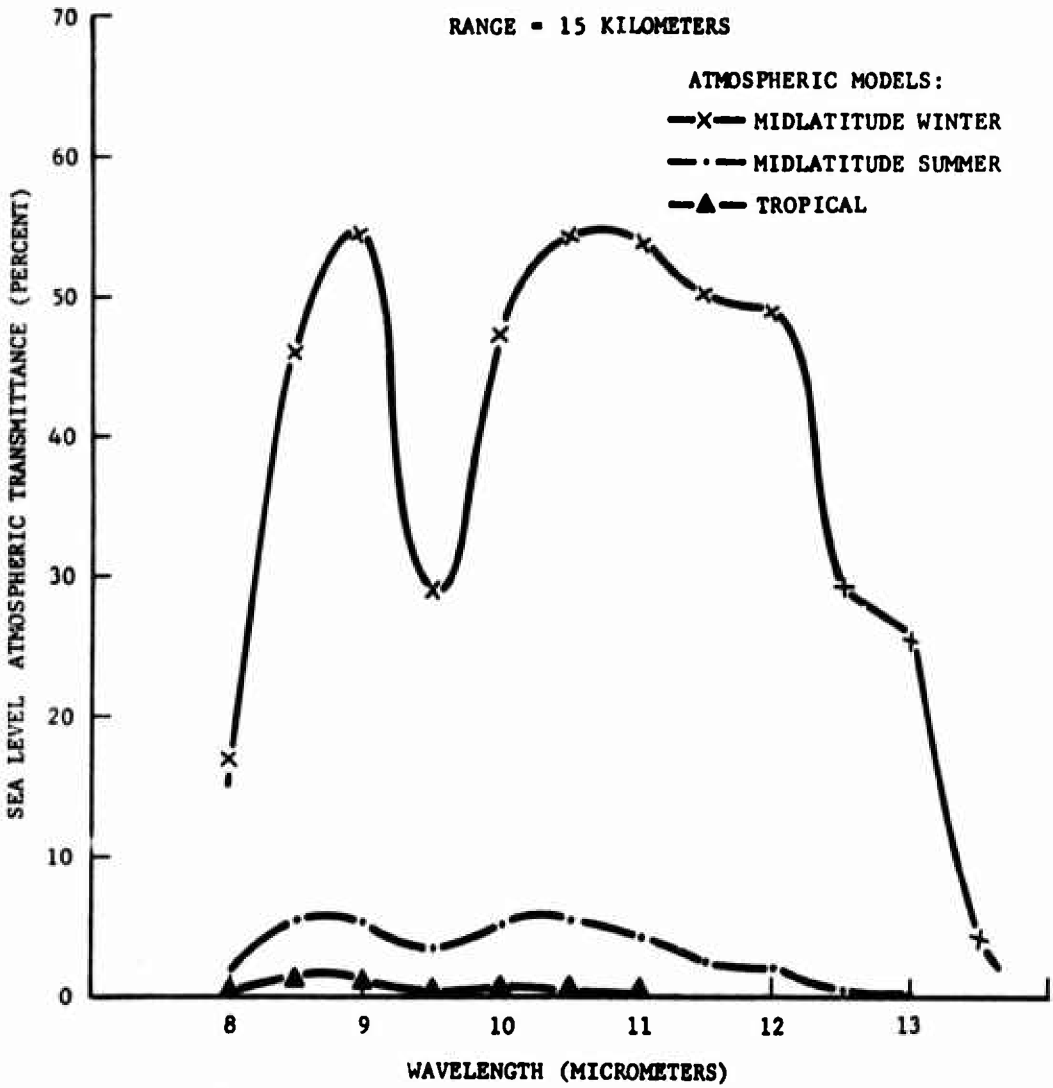


FIGURE 4.3-20. SEA LEVEL SPECTRAL TRANSMITTANCE IN 8 TO 14 μM WINDOW

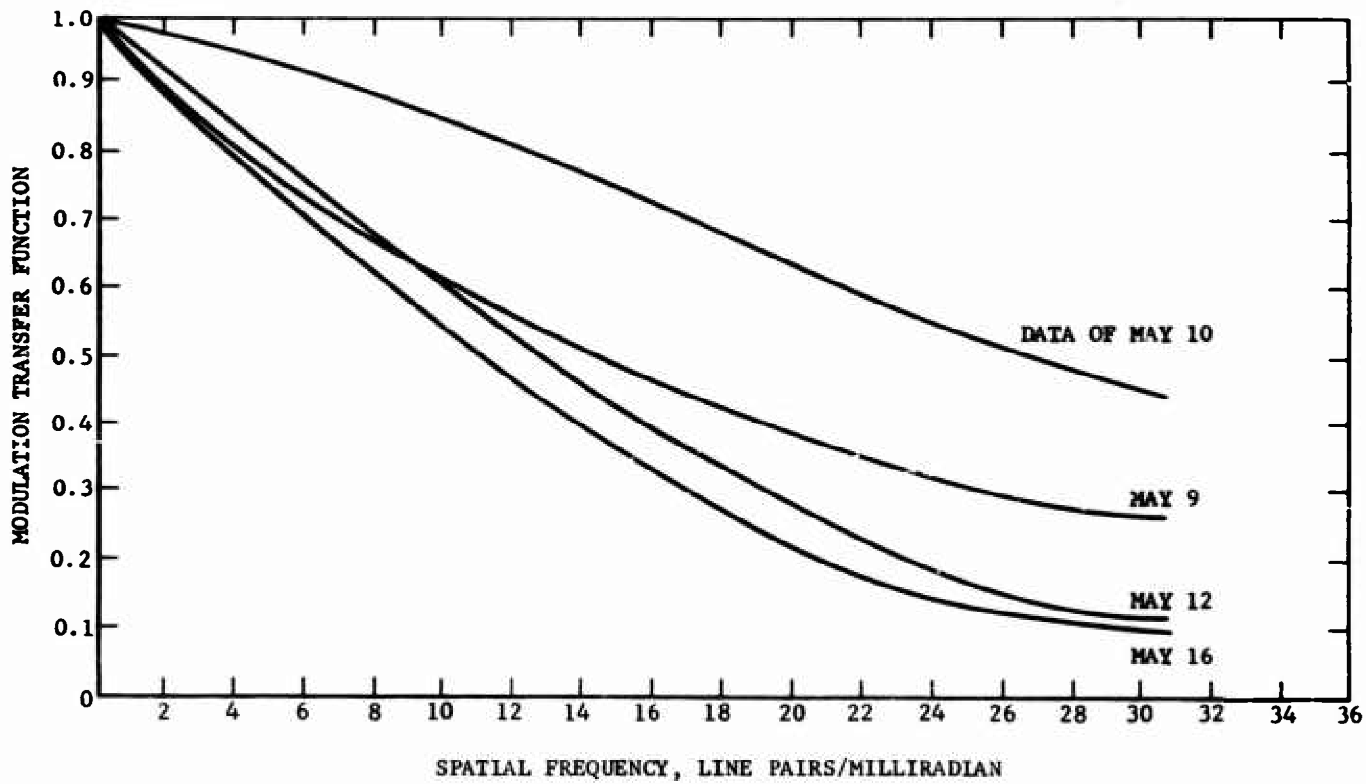


FIGURE 4.3-21. MTF DUE TO ATMOSPHERIC TURBULENCE [121]

For a horizontal path of sight, the function D is directly proportional to r, the range to the object to be viewed. Thus the MTF of a given atmosphere is a strong function of the viewing distance. In general, D is also a decreasing function of altitude so that the MTF of the atmosphere is better at higher altitudes. This means that if a terrestial target is to be viewed at a long slant range, the effect of atmospheric turbulence will be less severe if the target is viewed from a high altitude.

A quantitative assessment of atmospheric MTF is beyond the scope of this report; but in general, if a very fine resolution viewing system is to be used over a very long atmospheric path, the effect of atmospheric MTF must be considered.

4.4 OPTICS

Subsection 4.4 is an elementary introduction to optics and optical considerations as they relate to imaging systems. Concepts, including simple geometrical relationships, and terminology are presented and discussed. Sensor irradiance relationships and limitations of optical system imaging performance are presented. Types of optical systems commonly used in imaging systems are introduced.

4.4.1 GEOMETRICAL RELATIONSHIPS

The following discussion is built around the schematic use of a thin lens. The terminology and relationships however hold, at least to the first order, for more complex systems including both reflective and refractive systems. The target is assumed to be distant and the sensor lies in the image plane of the optics. Higher order effects are beyond the scope of this document.

4.4.1.1 Aperture, Entrance and Exit Pupils

Aperture is the useful opening in the optical system that accepts the radiation that forms the image. The larger the aperture, the more radiation or photons there are available for imaging purposes. For this reason, low light level systems provide as much aperture as can be allowed within cost and integration constraints. The element in the optical system which limits the size of the accepted ray bundle is called the aperture stop (see Figure 4.4-1). The image of the aperture stop from the object side of the system is called the entrance pupil, and because the entrance pupil determines what rays are accepted it is also called the clear aperture. Clear aperture is normally measured by its diameter. The image of the aperture stop from image side of the system is called the exit pupil. Usually in real time system applications where the target is distant (optical infinity) and the sensor is located at the focal point of the optics, the entrance pupil is the clear diameter of the first optical element. If an adjustable diaphragm or aperture is used to control the amount of light reaching the sensor, then the diaphragm becomes the aperture stop and its image in object space is the entrance pupil.

4.4.1.2 Focal Length

When parallel light (light from a distant source) enters an optical system parallel to the optic axis of the system, it is focused to a point called the focal point, and a perpendicular plane through that point is called the focal plane. However, with many systems the focused optical field will be curved, not flat. That quality of the imaging system which determines the focal point location and image size is the effective focal length.

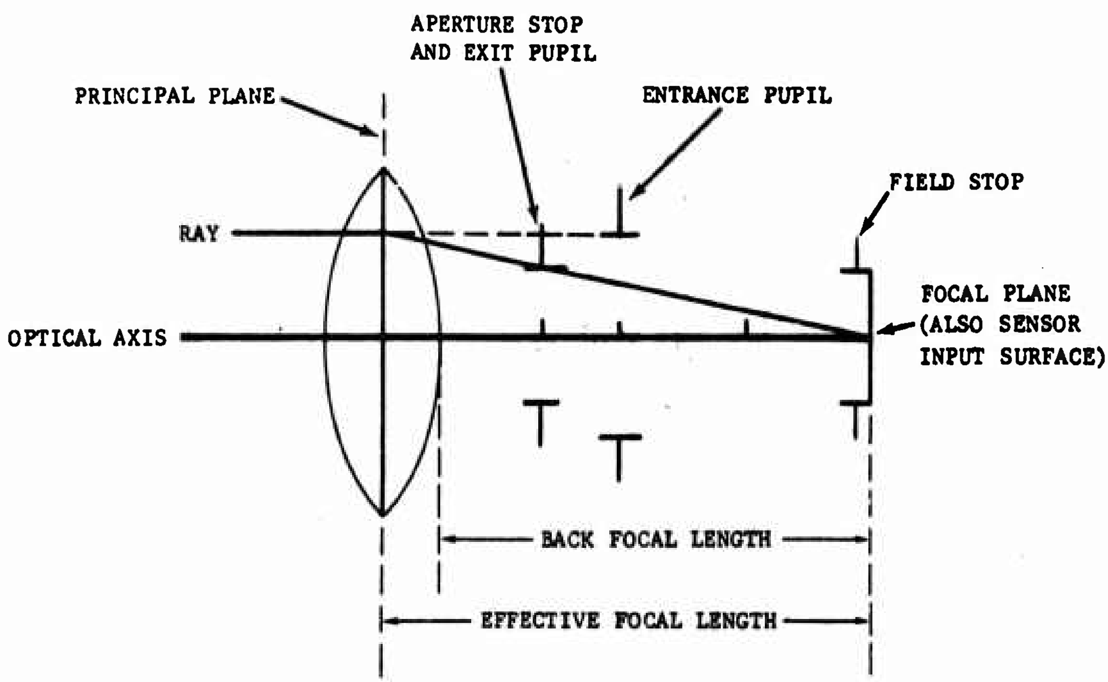


FIGURE 4.4-1. SIMPLE OPTICAL SCHEMATIC

The effective focal length is the distance from the focal point to its principal point. Each optical system has two principal points, although they may be superimposed as in the case of some thin lenses, and principal planes. As in the case of the focal plane, the principal planes in general are not flat and are not necessarily located physically within the optical system. The location of the focal point from the last optical element is the back focus and is needed to locate the sensor.

Most imaging applications are for distant targets and the sensor is located at the focal point. When the target scene is near, the focused image will be located beyond the focal point.

4.4.1.3 Field of View

There is one element in the optical system which limits the incident angle, with respect to the optic axis, of the ray bundle from the target scene. The limiting angle is called the field of view and the limiting element is called the field stop. The aperture stop is sometimes the field stop but in this case the edge of the field is not sharply defined. It is the usual practice to sharply define the field in the image plane by a mask. In the case of real time systems, the sensor is the field stop. In Figure 4.4-2 the angular field of view is defined as a function of sensor size and focal length. For small angles $p = d/f$ where d and f are expressed in the same units. The field of view as just defined is the total angular field for a circular field stop. It is also common, and usually confusing, to call the half field angle $p/2$ the field angle without specifying whether it is the total or half field. In the case of rectangular sensor such as the raster on a TV pickup tube, there is the angular field for the diagonal, the field for the horizontal dimension, and the field for the vertical dimension.

Confusion arises when the field of view is specified as a value without reference to the specific dimension to which it applies.

4.4.1.4 Image Size/System Magnification

The image size of a distant object in the optical field is a function of the input angle from the object and the focal length of the optical system. From Figure 4.4-2 it is apparent that the image size corresponding to angle p_2 is smaller at position f_1 and that the image size varies directly with the focal length. Image size is inversely related to the angular field of view (in Figure 4.4-2, $p_2 < p_1$). When an optical system is designed to provide a continuously variable field of view and focal length (over a limited range), it is said to be a zoom system from the appearance that the observer has "zoomed" in on the target. Discrete field changes are also possible and many systems are designed with multiple fields of view. The number of scan lines or resolution elements on the target also increases as the image is enlarged.

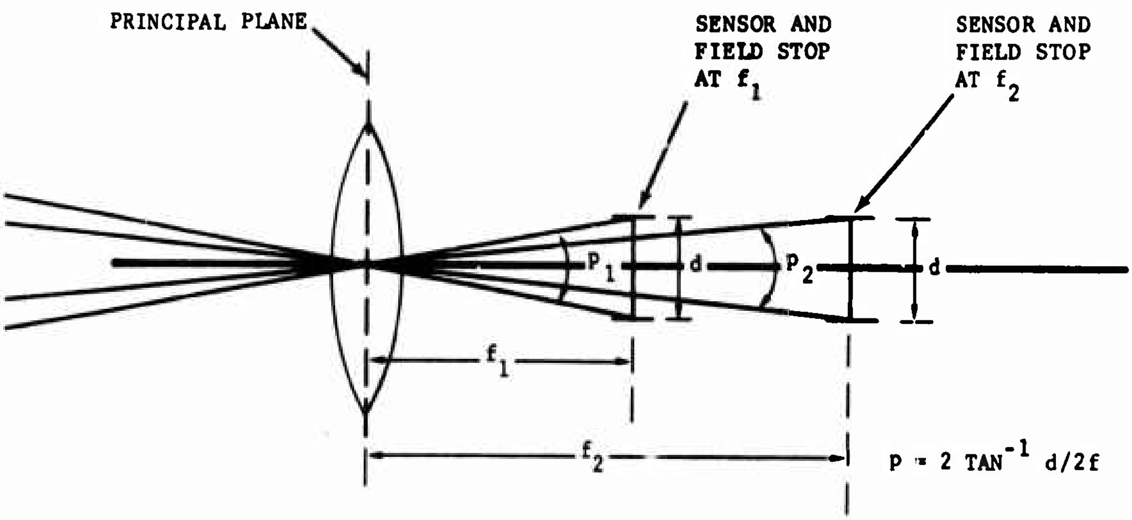


FIGURE 4.4-2. FIELD OF VIEW AND IMAGE SIZE

Increasing the focal length (or reducing the field of view) is one way to present a larger image to the observer. The size of the display and the viewing distance of the observer will also affect the image size. The system magnification is the ratio of the displayed target angle referenced to the observer to the actual target angle (Figure 4.4-3). The observer therefore has some control of the magnification by changing his viewing distance. This process is not without limit. Moving closer to the display to magnify target detail works to the point that additional movement reveals no new additional detail or information about the target. Even though the target will become larger the observer already has all the information he can obtain and in this case the increased magnification is called empty magnification.

4.4.1.5 f/Number, T-Number, Relative Aperture, Numerical Aperture and Speed

Relative aperture, numerical aperture, f/number, speed and T-number all refer to the same characteristics of an optical system which is a measure of the angular size of the image forming ray bundle (see Figure 4.4-4). The size of this ray bundle determines the energy density of focal plane irradiance of the image.

The f/number, sometimes written f/ or F is the ratio of the focal length to the clear aperture. $F = f/D$. Relative aperture is a synonym for F. The numerical aperture (NA) is defined in terms of the ray bundle half cone angle.

$NA = n'/n \sin u$ when n' and n are the indices of refraction for the materials containing the image and target object. If both are in air, then $NA = \sin u$ and the NA can be related to F by

$$NA = \left(\frac{1}{2}\right)\left(\frac{D}{f}\right) = \frac{1}{2F}$$

Although it is common to discuss the "speed" of a system in terms of its f/ (i.e., f/2 is "faster" than f/4), the "speed" refers to how fast the exposure of an image on film can be accomplished and is therefore proportional to the inverse square of the F or T number (see Paragraph 4.4.2).

The f/ does not account for light losses through the optical system; and if these are significant the irradiance values based upon f/ calculations will be in error. To account for transmission losses the T-number is used and it is related to F by

$$\text{T-number} = \frac{F}{\sqrt{\tau}}$$

where τ is the optical system transmission.

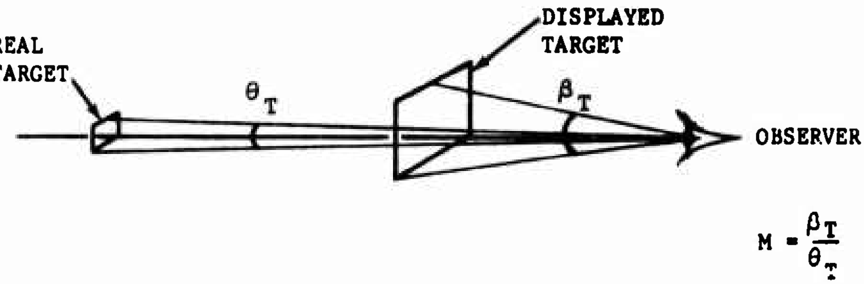


FIGURE 4.4-3. SYSTEM MAGNIFICATION

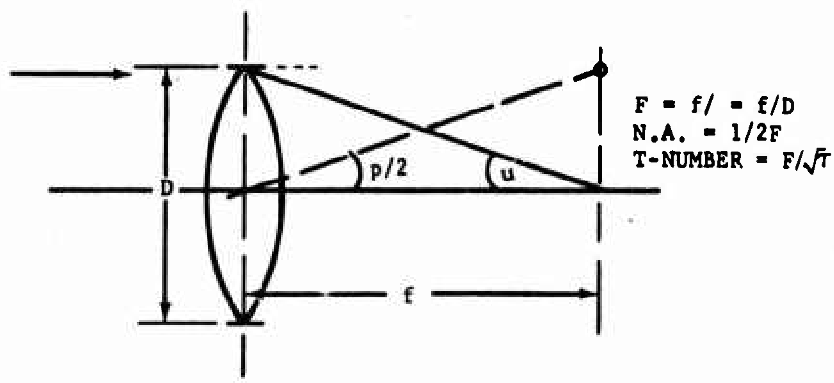


FIGURE 4.4-4. IMAGE PLANE IRRADIANCE

4.4.2 IMAGE PLANE OR SENSOR IRRADIANCE CONSIDERATIONS

The on axis value of image irradiance is given by

$$E = \pi L \, T/(2F)^2 \, *$$

where L is the scene radiance in the appropriate units. If E is in watts cm^{-2} when L is in watts cm^{-2} ster $^{-1}$. This relation holds when the angle of the incidence bundle is small enough that tan u ≈ sin u (Figure 4.4-4) and the image is formed close to the focal point. For larger angles the correct relationship is

$$E = \pi L \, T \sin^2 u$$

Either equation demonstrates the only parameters that determine the image irradiance are the input irradiance at the entrance pupil, the transmission of the optics, and the exit slope angle u.

The image irradiance and the sensor response to the image irradiance determine the input signal to the imaging system.

4.4.2.1 Off-Axis Irradiance

For an object that would produce an on-axis irradiance of E, the off axis irradiance would be

$$E' = E \cos^4 p \quad \text{(Figure 4.4-4)}$$

(79) Near the axis the $\cos^4$ p factor varies only slightly but when p is 30 degrees the irradiance is reduced by 44 percent.

In a system containing stops the problem known as vignetting may occur. (The vignetting may be deliberate as in the case of a field stop at the image plane.) For fields of view subtending larger angles than p in Figure 4.4-5, some rays from the field will miss the optical element as in the case of ray a, while at the same time the stop prevents other rays from reaching the optical element. The larger the incident angle, the more the ray bundle is vignetted with a corresponding loss in image irradiance off axis.

*When the units are lamberts or foot lamberts, the factor of π does not apply and $E = L \, T/(2F)^2$.

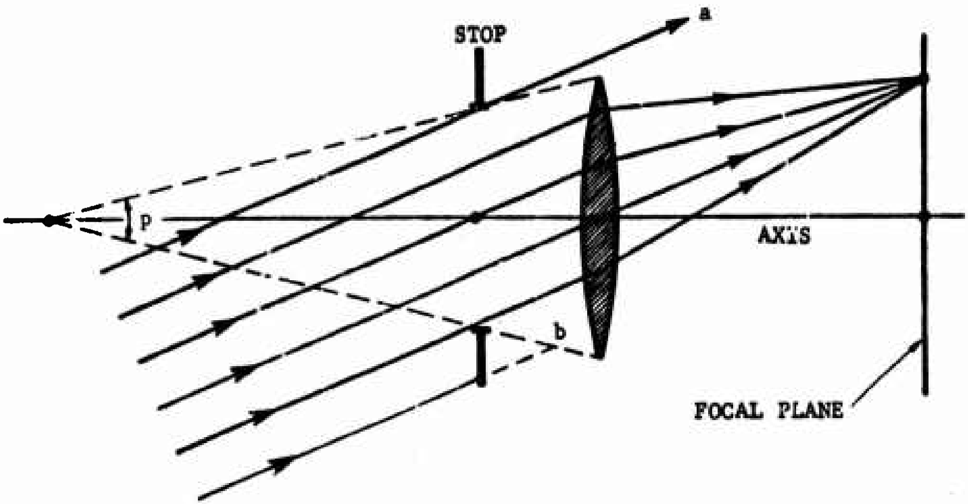


FIGURE 4.4-5. VIGNETTING

4.4.3 LIMITATIONS TO OPTICAL SYSTEM PERFORMANCE

Optical systems are limited by two mechanisms in their ability to form ideal images of the target scene. One mechanism, the result of the nature of the optical components and surfaces in the optical system, is the failure of the optical system to image all rays entering the optical system from the same point on the target onto the corresponding point in the image. The resulting image defects are called aberrations. The other mechanism is due to the wave like nature of light which results in a fundamental limitation as to the ability to image fine detail. This mechanism is called diffraction. Aberrations are to a large extent controllable by the optical designer subject to cost and size limitations. Diffraction is a physical effect that is not subject to reduction and always represents the maximum level of performance that can be achieved (i.e., one can do no better than a diffraction limited optical system).

4.4.3.1 Aberrations

The path of a ray through a refractive (lenses) optical system is determined by Snells law which describes the change in ray direction at air/glass interfaces. (Snells law is equally applicable to interfaces between other optical media.) Snells law in equation form is $n' \sin \phi' = n \sin \phi$ where ϕ, ϕ' are the angles described in Figure 4.4-6 and n' and n are the indices of refraction of the interfacing materials. The index of refraction is the optical property of materials that determines the speed of

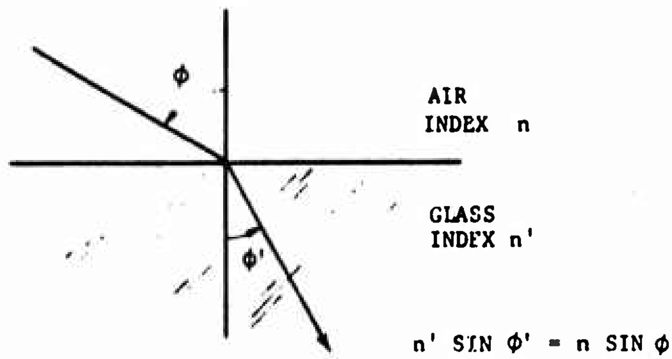


FIGURE 4.4-6. SNELLS LAW

light through that medium. The index of air is approximately n = 1 while that of glass depends upon the type of glass, but n' = 1.5 is a typical value.

In order to describe lens aberrations the sine terms used in ray tracing are expanded in a power series and the lens designer uses as many terms as he requires to adequately describe the image. The expansion is

$$\sin \phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} \ldots$$

When ϕ is small the image relationship can be determined from $\sin \phi = \phi$ at which time it is said to form the basis of first order theory. When the second expansion term is included one is working in third order theory.*

*Rarely did the designer worry about image imperfections beyond fifth order theory due to the mathematical complexity of the equations involved in describing the image and the relative insignificance of these terms in determining the properties of the image (i.e., they are negligible). Now with the digital computer to aid him, the designer can easily graphically trace what rays he needs to design and optimize his optical system.

The equations resulting from third order theory give a fairly accurate account of the deviations from first order theory. Sidel was instrumental in determining these deviations or aberrations from first order theory, and in recognition of his work the third order aberration terms are called Seidel aberrations. There are five monochromatic (single colored light) aberrations defined by Siedel's work:

(1) Spherical

(2) Coma

(3) Astigmatism

(4) Field curvature

(5) Distortion

Jenkins and White (79) or Smith, standard texts on optics, treat aberration in detail with fair simplicity.

Spherical aberrations arises from the fact that different parts or zones of the lens have different focal points (see Figure 4.4-7). Coma and astigmatism are off-axis defects and field curvature implies the focused

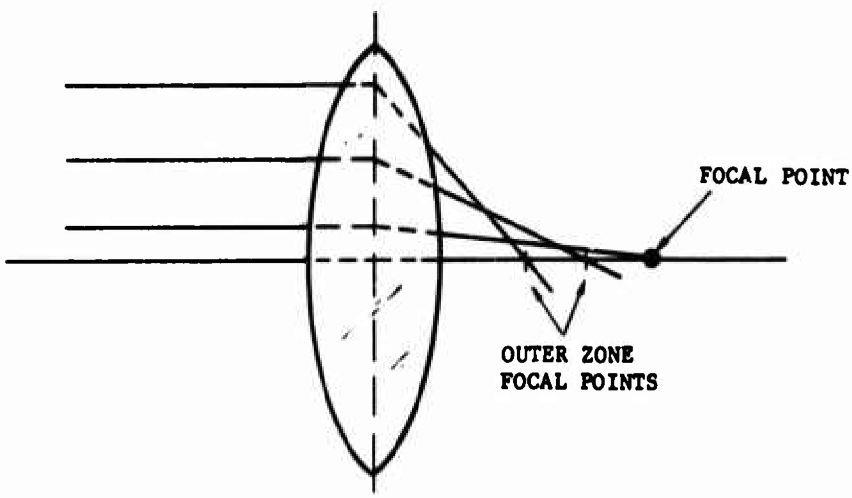


FIGURE 4.4-7. SPHERICAL ABERRATION

image does not lie in a plane but in a curved surface symmetrical about the optical axis. Figure 4.4-8 shows the effects of distortion.

In addition to the 5 monochromatic aberrations, refractive optics also suffer from chromatic aberration. Chromatic aberration arises from the fact the index of refraction of the refractive components (lenses) is not constant with the wavelength (Figure 4.4-9) of the incident light. As a result the different colors of the scene come to a focus at different axial locations with different image sizes (see Figure 4.4-10). The former condition is called longitudinal chromatic aberration while the latter condition is lateral chromatic aberration.

Reflective optical components are free from chromatic aberrations unless they are overcoated with a substantial thickness of refracting material. Reflective mirror coatings will however affect the spectral content of the image as the material reflectivity is not constant with wavelength. Reflective components do suffer monochromatic aberration in a manner similar to lenses.

Combinations of optical elements can reduce the aberration inherent in a single element. As an example refractive optics can be used to correct spherical aberration in spherical mirrors and combinations of glass are used in refractive systems to reduce chromatic aberrations.

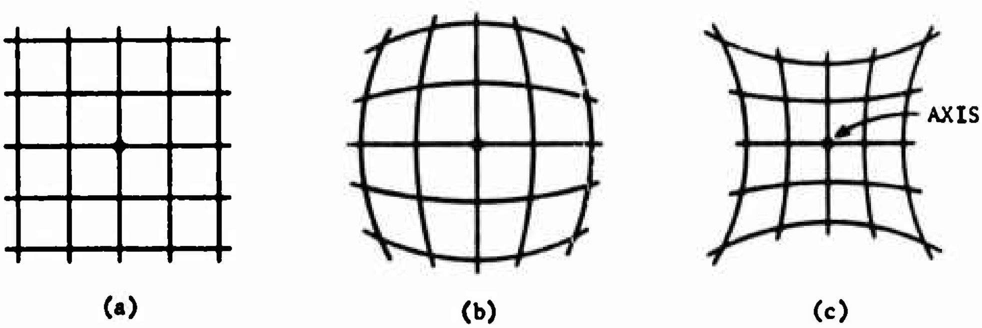


FIGURE 4.4-8. IMAGES OF A RECTANGULAR OBJECT SCREEN SHOWN WITH (a) NO DISTORTION, (b) BARREL DISTORTION, AND (c) PINCUSHION DISTORTION

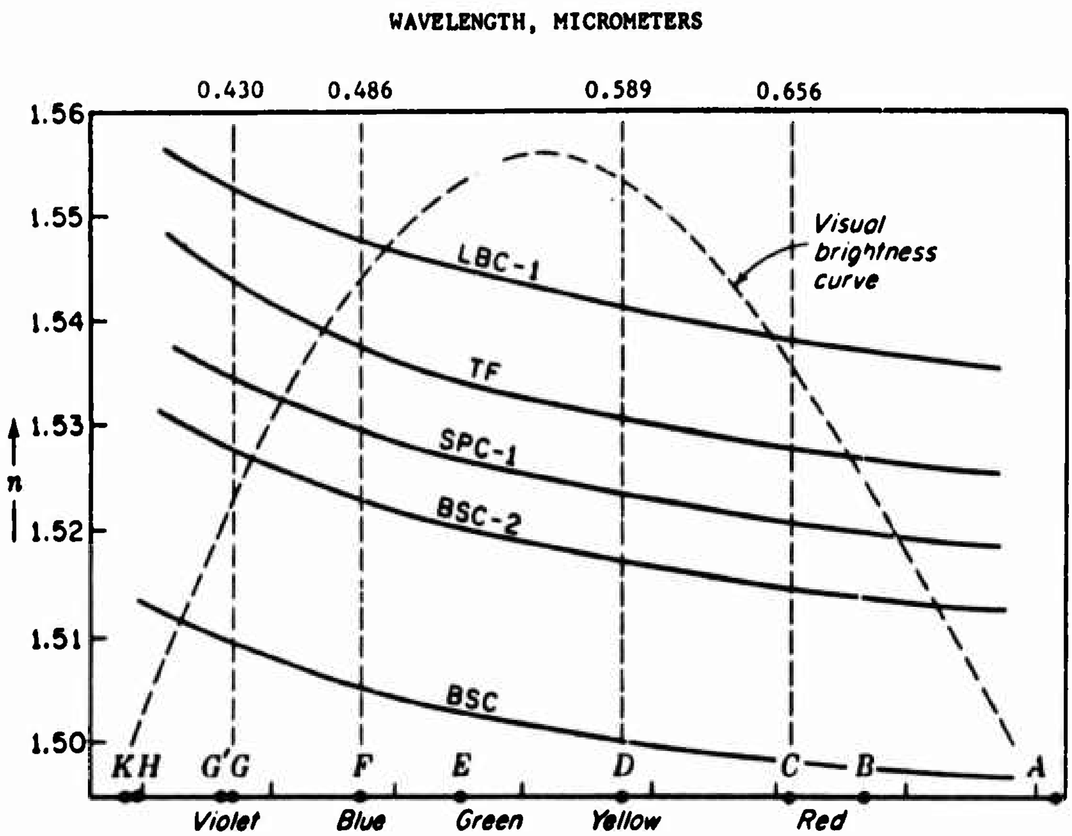


FIGURE 4.4-9. GRAPHS OF THE REFRACTIVE INDICES OF SEVERAL KINDS OF OPTICAL GLASS. THESE ARE CALLED DISPERSION CURVES (79)

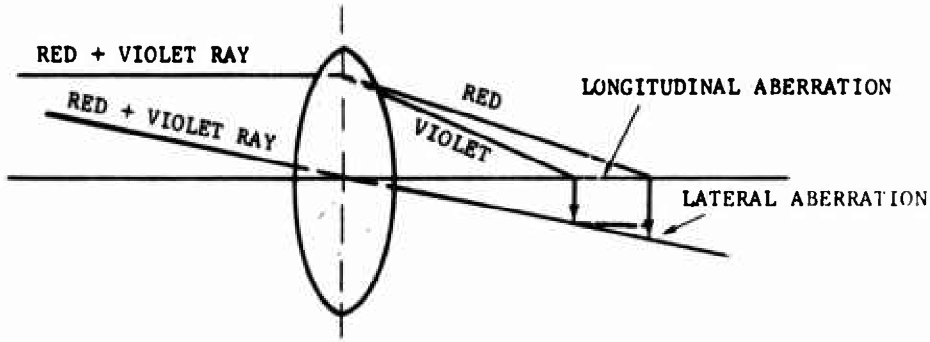


FIGURE 4.4-10. CHROMATIC ABERRATION

4.4.3.2 Diffraction/Wavefront Distortion/MTF

As a wave of light passes through an aperture, that portion of the wave passing through the aperture will diverge (Figure 4.4-11). Optical elements may redirect the wavefront but they cannot compensate for the divergence resulting from the aperture. If a plane wave is focused, the resultant radiant distribution in the image is called a diffraction pattern. The shape of the pattern is a function of the shape of the aperture. The diffraction pattern for a circular aperture is shown in Figure 4.4-12. It has a bright core with alternating dark and light rings. The diffraction pattern combines with optical aberrations and the scene radiance distribution to determine the image irradiance distribution. For circular apertures it is conventional to consider the diameter of the first dark ring as the limit of resolution and the angular value of this diameter is for monochromatic radiation

$$\delta = 2.44\ \lambda/D$$

where D is the diameter of the aperture and λ has the same units as D. Note the diffraction spot (or limit) is a function only of the wavelength and aperture size. With FLIR systems where the wavelengths are fairly long (12μ) diffraction effects in the optics become a major consideration.

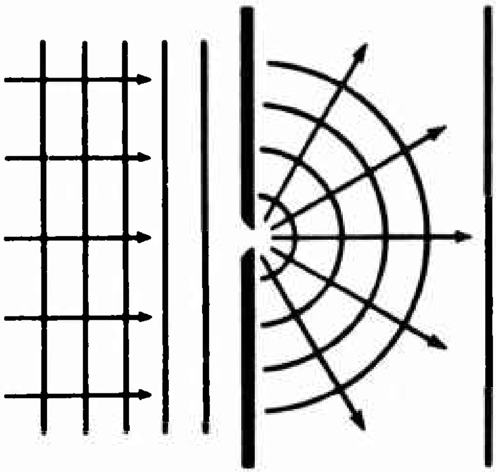


FIGURE 4.4-11. DIFFRACTION OF WAVES AT A SMALL APERTURE (79)

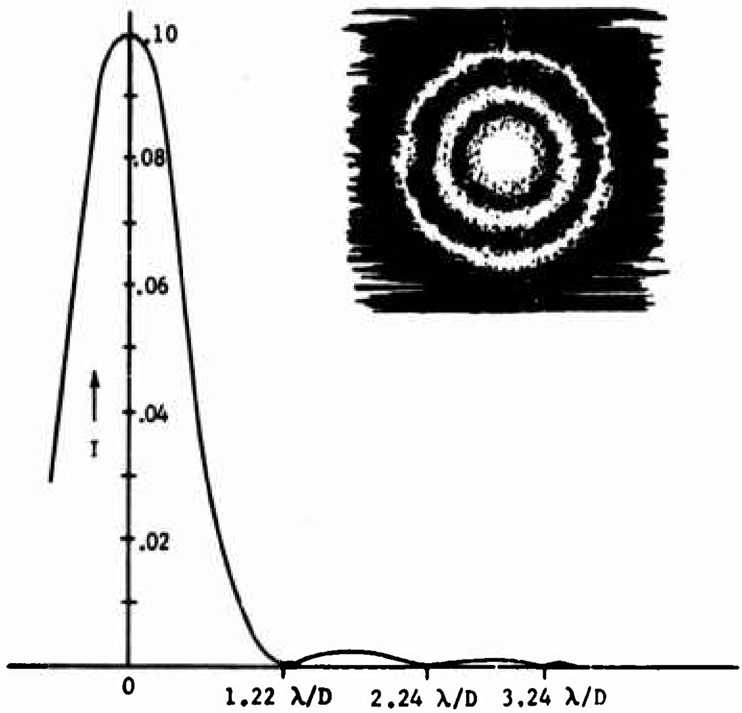


FIGURE 4.4-12. DIFFRACTION PATTERN OF A CIRCULAR APERTURE (85)

In addition to diffraction effects, the aberrations of an optical system distort the incident wavefront. In most cases it is aberration rather then diffraction that determines the limiting capability of the optical system.

When aberration is small and both aberration and diffraction determine imaging performance, the wavefront distortion due to aberration or mis-focus is measured in a unit called a Rayleigh limit. The value of a Rayleigh limit is a $\lambda/4$ path length difference between the actual wave and the "perfectly" converging wavefront converging upon the paraxial focus (see Figure 4.4-13 and Smith).

The effect of diffraction and small amounts of aberration upon system MTF* (3.3) have been published (85, 84) and are reproduced in Figures 4.4-14 and 4.4-15. Figure 4.4-16 shows the effects of circular obscurations, as in a Cassegrain optical system, upon system MTF (see Section 3.3). The units of the abscissa are normalized spatial frequency relative to the cutoff frequency of the optical system. The cutoff frequency is that spatial frequency (see Section 3.3) at which diffraction effects reduce the modulation that was present at the system input to zero modulation in the image. The cutoff frequency ν_o is

$$\nu_o = \frac{1}{\lambda(f/\text{number})}$$

and ν_o is in cycles per millimeter if λ is in millimeters.

4.4.4 TYPES OF OPTICAL SYSTEMS AND COMPARATIVE ADVANTAGES

The basic types of imaging optics are refractive which consists of lenses, reflective which consists of mirrors, and catadioptric which consists of both refractive and reflective elements. Well known designs of any of the systems may be referred to by name such as Cassegrain, which is a reflective system, or Schmidt which is a catadioptric system.

4.4.4.1 Refractive Systems

Chromatic aberration is the most significant limitation to refractive systems for use with wide spectral bands. With some difficulty and sacrifice in angular coverage, it is possible to cover a 2:1 range of spectral values (as an example, 0.5 micrometers to 1 micrometer). In practice it is difficult to achieve an f/ smaller than 0.9; but for large fields (>40° total field) with good chromatic aberration and reasonable cost, f/ equal 1.5 represents a reasonable limit. A refractive system is illustrated in Figure 4.4-17.

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*MTF is a measure of the systems ability to reproduce fine scene detail in the image.

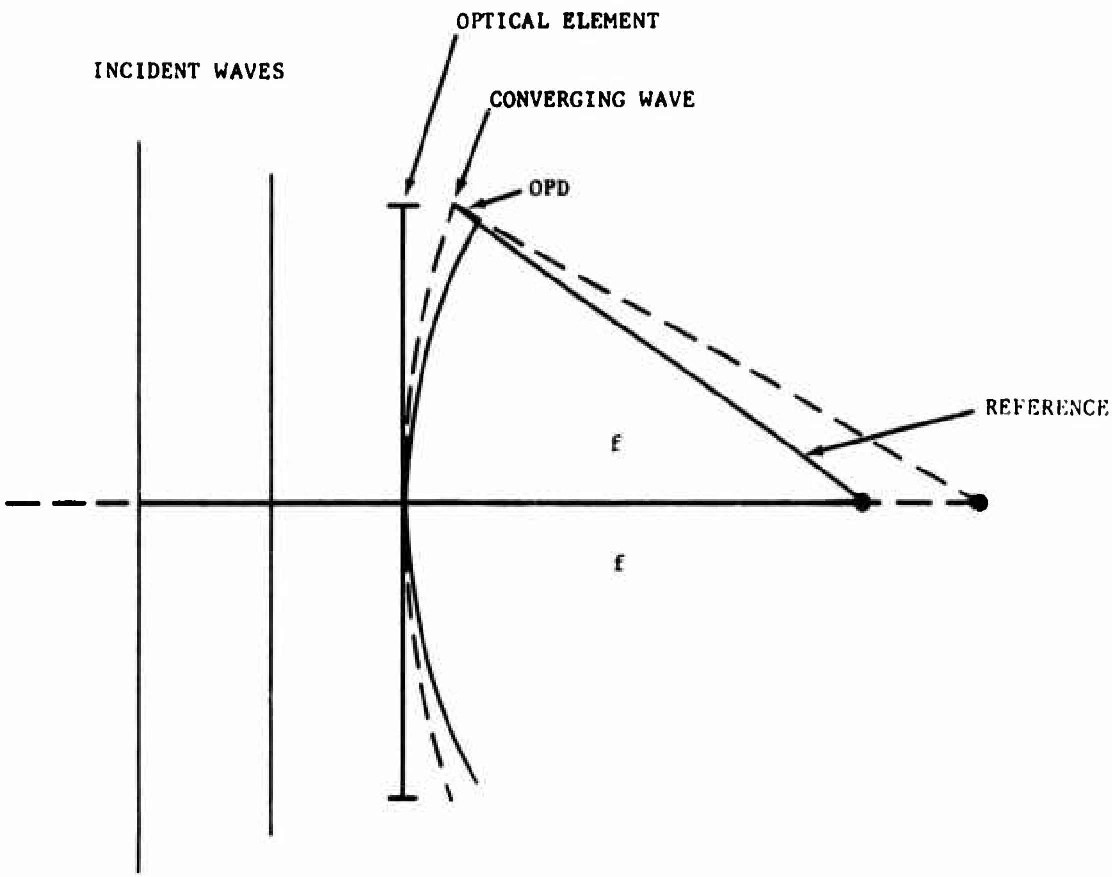


FIGURE 4.4-13. WAVE FRONT DISTORTION

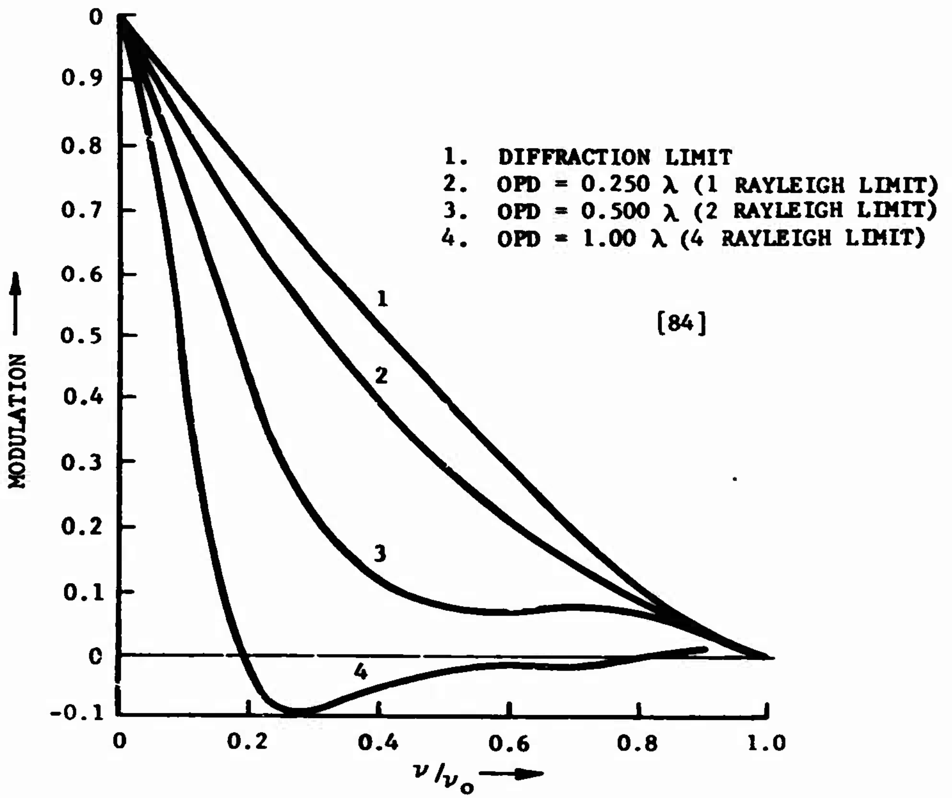


FIGURE 4.4-14. DIFFRACTION LIMITED PERFORMANCE FOR CIRCULAR APERTURES INCLUDING SMALL AMOUNTS OF DEFOCUSING (84)

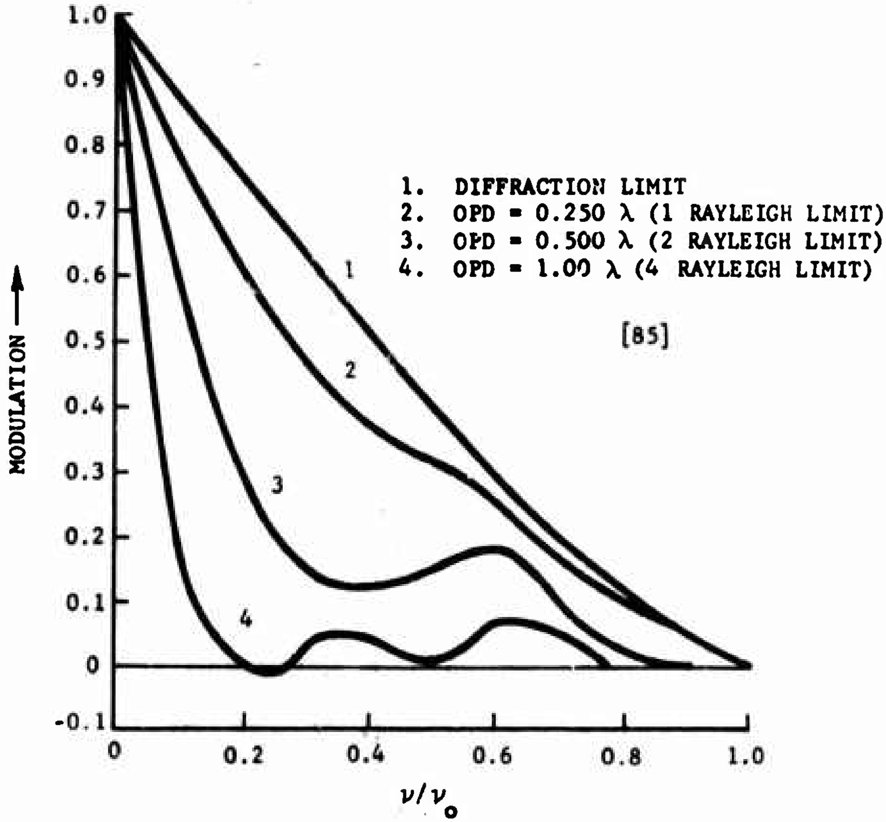


FIGURE 4.4-15. DIFFRACTION LIMITED PERFORMANCE FOR CIRCULAR APERTURES INCLUDING SMALL AMOUNTS OF THIRD ORDER SPHERICAL (IMAGE PLANE MIDWAY BETWEEN MARGINAL AND PARAXIAL FOCUS) (85)

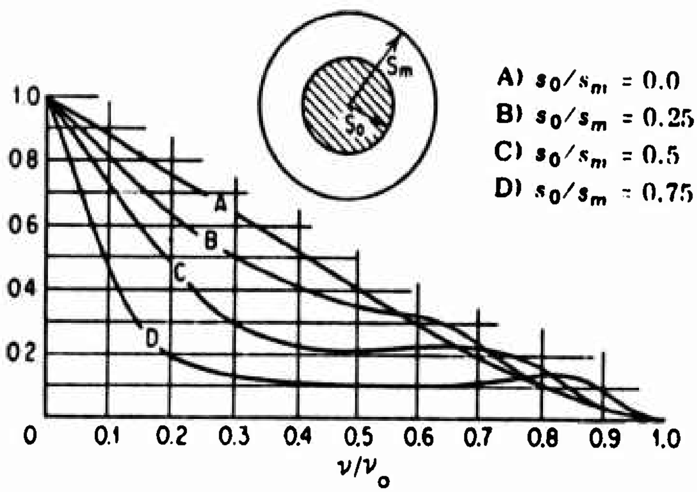


FIGURE 4.4-16. THE EFFECT OF A CENTRAL OBSCURATION ON THE MODULATION TRANSFER FUNCTION OF AN ABERRATION FREE SYSTEM (85)

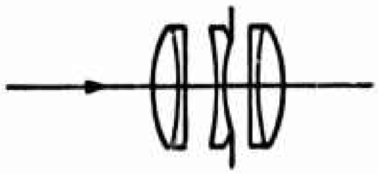


FIGURE 4.4-17. REFRACTIVE SYSTEM

4.4.4.2 Reflective Systems

Reflective systems have the advantage of the absence of chromatic aberration over the useful spectral range of the reflecting material. Reflective systems have good imaging performance over very small fields of view. The maximum useful field is from two to four degrees total field. An example of a reflective system is illustrated in Figure 4.4-18.

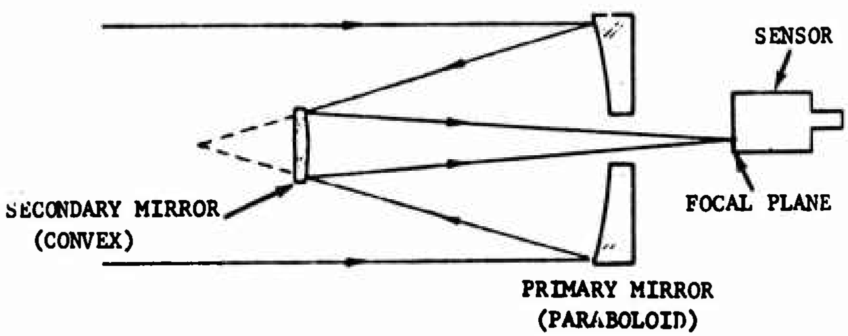


FIGURE 4.4-18. REFLECTIVE SYSTEM (CASSEGRAIN)

4.4.4.3 Catadioptric Systems

Spectral range generally is superior to the totally refractive system since the refractive elements of a catadioptric system contain little power. The catadioptric system can be made with fields of view (total) up to 10 degrees but size becomes a problem. The image field is curved and the sensor must be designed to accommodate the curved image as is illustrated in the example catadioptric system in Figure 4.4-19.

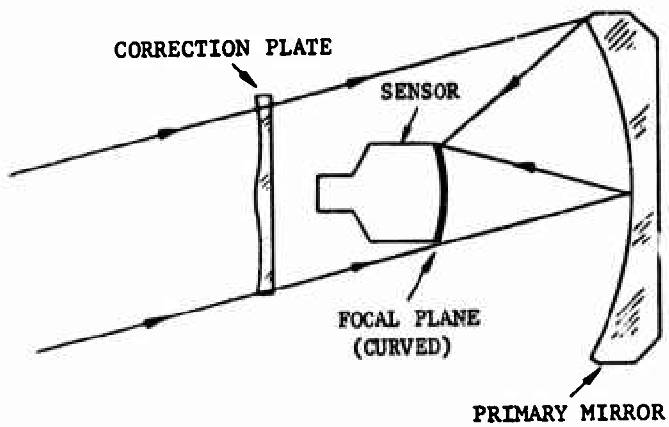


FIGURE 4.4-19. CATADIOPTRIC SYSTEM (SCHMIDT SYSTEM)

4.4.5 MISCELLANEOUS OPTICAL CONSIDERATIONS

4.4.5.1 Veiling Glare, Sealing, and Coatings

Veiling glare is the extraneous light reaching the image plane that masks the image. It can be caused from light leaks in the optical cell, strong light sources both outside and inside the field of view, poor baffling and scattering of the image radiation by scattering centers in the optical system itself. Any veiling glare will reduce the image contrast and care should be taken to minimize its effects.

Optical systems are often sealed and filled with an inert gas such as nitrogen. Sealing keeps dust from entering the system and contributing to veiling glare, and the inert atmosphere prevents fogging of the optics due to normal humidity in the air. Most optics are coated to prevent contamination of the optical surfaces and to reduce reflection losses. Antireflection coatings enhance the optical transmission of the system while at the same time reducing the amount of reflected radiation that can contribute to glare.

4.4.5.2 Fiber Optics

An individual fiber optic relays a ray of light from one point in an optical system to another. If a large number of small fibers are combined in a bundle in such a way that the location of each fiber at the output end is the same as it is at the input, an image may be transmitted. Fiber optics

are commonly used in this manner as faceplates for intensifiers and television pickup tubes. The faceplate's primary purpose is to transport the image into the vacuum enclosure with small light loss. Fiber optics are nearly equivalent to a zero thickness window. In addition, the faceplate may be shaped to conform to the curved image of an optical system and convert the curved image into a flat one for the sensor.

4.4.5.3 Size and Cost Considerations

Generally the cost of an optical system increases as:

(1) The field of view grows larger

(2) The f/ becomes smaller (faster) (but note theoretical resolution falls with increasing f/)

(3) Variable focal lengths are required

(4) Finer resolution is required

(5) Mechanical tolerances are tightened

(6) The spectral bandwidth increases

(7) Tricky or nonconventional designs are required (such as telephoto systems)

(8) Physical size grows

As a first order effect, the lens volume for a system with a given field of view and f/ is proportional to the cube of the image size. Aperture and image size must then be considered in a trade-off study with required resolution performance. (Section 4.7) (42)

4.4.5.4 Unique Problems

FLIR systems are sensitive to radiation from all thermal sources radiating in the detector spectral response band. This unfortunately includes the FLIR optics, baffles, cell assemblies and any other piece of hardware which appears in the detector field of view. This unwanted radiation is a noise source and it will mask the image. To combat these undesired sources of radiation, a field stop is constructed in front of the detector. The stop is cooled so that it is not a significant radiation source itself. It is thus called a cold stop. The acceptance angle of the stop is sufficiently large to accept the incident ray bundle while excluding as much of the warm background as is practical.

The materials used in thermally imaging systems are more exotic than those used in TV systems. Many IR materials are hygroscopic and must be protected from atmospheric moisture.

In LLLTV systems where several stages of intensification are used, there will exist a very high (voltage) potential with respect to ground at the face of the first intensifier. The optics/tube interface must consider the high voltage breakdown problem.

4.4.5.6 Checklist

The following is a list of optical system parameters that may need to be considered by the system engineer:

- focal length
- spectral band
- target distance
- angular field of view
- MTF/resolution
- f/, T-number
- material requirements
- interface requirements
- mechanical constraints
- tolerances and costs
- environment
- size

4.5 SENSORS

Subsection 4.5 describes the devices by which the radiant image of the scene is transformed (tranduced) into an electrical analog. Three kinds of devices are covered: direct view sensors, television sensors and FLIR sensors. The physical construction; spectral properties, and spatial properties of several types of direct-view and television devices are discussed. The make-up of the FLIR system is described and spatial/sensitivity properties of FLIR sets are considered.

4.5.1 GENERAL

The electro-optical sensor converts the photon image formed by the objective optics into an electronic signal. This electronic signal is then processed by a suitable display to recreate a visible image for viewing by an observer.

E-O sensors can be divided into three broad classes:

(1) Direct view imaging devices

(2) Television systems

(3) Forward Looking Infrared (FLIR) systems

The first two classes generally work in the visible or near infrared portion of the spectrum, while the FLIR systems generally work either in the 3 to 5μm or the 8 to 14μm atmospheric transmission windows. The visible and near IR systems use radiation reflected from the scene. Direct view and TV systems are therefore dependent upon a source of illumination such as the sun, the moon, or a searchlight. FLIR systems depend upon radiation emitted from the scene and consequently do not require such an external illuminator as a source of photons for the image.

The sensor descriptions which follow are intended to present only a rudimentary understanding of sensor performance. For more detailed descriptions of direct view and TV sensors, the books by Biberman and Nudelman (99) and (100) are recommended.

4.5.2 DIRECT VIEW SENSORS

4.5.2.1 Sensors

Direct view sensors are referred to as either image intensifiers or image converters. Image intensifiers work in the visible spectrum while image converters accept inputs in the near infrared or ultraviolet spectrum and display a visible output.

In a direct view device, the objective lens forms an image on the photocathode of the intensifier. (If a fiber optic faceplate is employed, the image is formed at its input and transmitted to the photosurface (see 4.4.5.2).) The photocathode is a photoemissive material which emits electrons in response to photons (light quanta) which are absorbed. The quantity of photoelectrons is proportional to the number of photons arriving at the photocathode. These photoelectrons are accelerated by an electric or magnetic field toward the anode of the intensifier. An electron optical system focuses the photoelectrons into an image on a phosphor screen, which in turn emits photons proportional to the photoelectron density.

In the "first generation" image intensifiers, the photoelectrons are accelerated through a high electric field (typically 15 kv) to strike the phosphor (Figure 4.5-1). The energy of the arriving photoelectrons and the quantum yield of the phosphor are such that the number of photons in the phosphor image is much greater than the number of photons in the optical image formed by the objective lens. Thus a brightness gain, typically on the order of 50 to 100, is achieved. Two or three stages of first generation intensifiers are often "cascaded" by fiber optic coupling, to provide brightness gains of 35,000 or more.

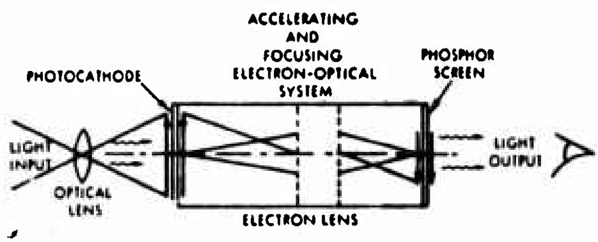


FIGURE 4.5-1. SCHEMATIC OF IMAGE INTENSIFIER (21)

So called "straight-through" intensifiers have nominally 1:1 magnification between input and output images. Others reduce the image size, and as a result the brightness gain increases by increasing the photoelectron density at the phosphor screen. Typically, this type of intensifier can be electronically zoomed. For example, an 80/25 intensifier has an 80mm diameter photocathode and a 25mm diameter phosphor. In normal operation, all of the image on the 80mm input is presented on the 25mm output. At full zoom, only the central 25mm of input is presented on the output so that a 3:1 zoom is available.

Display intensifiers are now available which magnify the electron image to a size that the output phosphor can be viewed directly without the need for an eyepiece. Display tubes with 25mm inputs and 125mm outputs are available. This magnification is accomplished at the expense of brightness gain.

For use with active pulsed illuminators or for stroboscopic applications, gateable image intensifiers are also available. Gating is usually accomplished by adding a gating electrode which, when gated "off", is made more negative than the photocathode so that photoelectrons cannot travel to the anode.

"Second generation" image intensifiers are based upon use of microchannel electron image multiplier plates. A microchannel is a hollow tube less than 0.001 inch in diameter. The inside surface is secondary electron emitting material. As a single photoelectron leaves the photoemissive surface, it enters the channel and collides with the wall, and secondary electrons are emitted. These secondaries are accelerated along the channel, creating additional secondaries. Electron gains of up to 10,000 are achieved. An intensifier is formed by assembling many microchannels side by side and placing this array between a photoemissive surface and a phosphor. This type of intensifier is called a "second generation" intensifier or a MCP intensifier. Other secondary electron multipliers are also used. (See Chapters 5 and 6 of (100).)

4.5.2.2 Spectral Responsivity and Luminous Sensitivity

Spectral responsivity curves of the more commonly used photoemitters are shown in Figure 4.5-2 (107). At the present time there is considerable effort in the development of gallium arsenide and related compounds as photoemitters for improved efficiency in the near infrared. Physical limitations in photoemissive materials limit the maximum useful wavelength to approximately 1.2 micrometers.

Peak quantum efficiencies in excess of 30 percent have been realized at shorter wavelengths. Quantum efficiency is the ratio of photoelectrons emitted to photons incident. While 100 percent quantum efficiency is theoretically possible, 50 percent seems to be a practical upper limit.

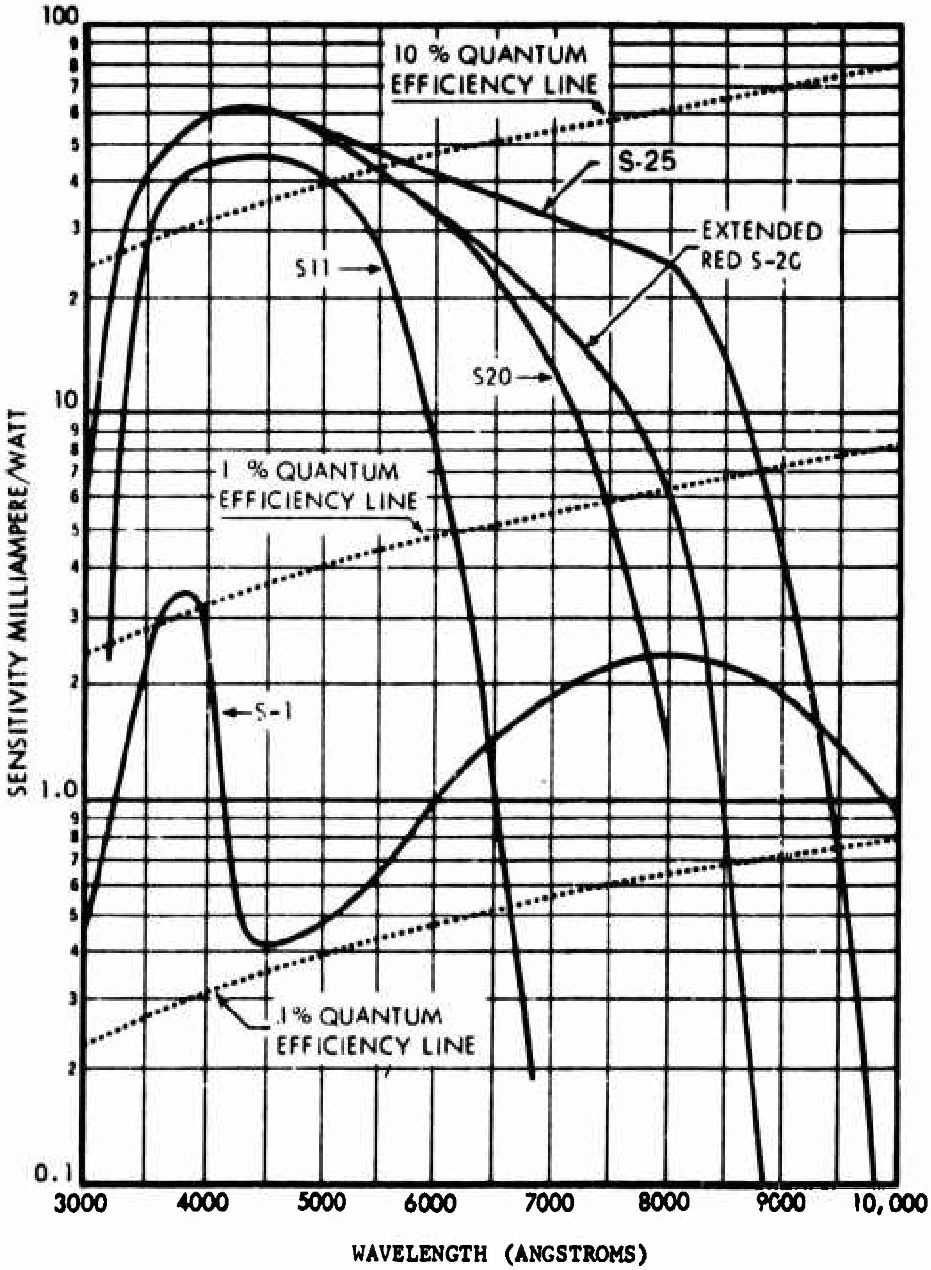


FIGURE 4.5-2. TYPICAL ABSOLUTE SPECTRAL RESPONSE CHARACTERISTICS OF VARIOUS PHOTOCATHODES (107)

See Chapter 8 of (99). The relationship between spectral responsivity and quantum efficiency is given by

$$\eta = \frac{124\ R_\lambda}{\lambda} \qquad (4.5\text{-}1)$$

where

η_q is quantum efficiency in percent,

R_λ is spectral responsivity at wavelength, λ, amps watt^{-1},

λ is wavelength, micrometers.

Image tubes are commonly rated in terms of their luminous sensitivity, in amperes per lumen of flux. The luminous flux source is understood to have a color temperature of 2870 K. Luminous sensitivity is an unfortunate, improper, and confusing rating for a device which has a spectral response curve different from that of the human eye (see Appendix A). It derives from the convenience of using an incandescent lamp as the illuminating source for sensor testing. The situation is not likely to change in the near future. Luminous sensitivity to a particular source can be related to spectral responsivity as follows. First, the photocurrent produced in response to the source is

$$i_{pc} = A_{pc} \int_0^\infty E_\lambda R_\lambda \, d\lambda \ \text{amperes} \qquad (4.5\text{-}2)$$

where

A_{pc} is photocathode active area, cm^2,

E_λ is photocathode spectral irradiance, watts cm^{-2} μm^{-1},

R_λ is photocathode spectral responsivity, amps watt^{-1},

λ is wavelength, μm.

This should be the only calculation which is necessary to establish the sensitivity of a given sensor in viewing a given source. To relate to luminous sensitivity, however, it is necessary to perform one more integration, which relates luminous flux to radiant flux, for the particular source in question

$$E_V = 680 \int_0^\infty E_\lambda V_\lambda \, d\lambda \ \text{lumens cm}^{-2} \qquad (4.5\text{-}3)$$

where

E_V is illumination, lumens cm^{-2}

680 is luminous efficacy of the photopic eye at the peak of its spectral sensitivity curve, lumens $watt^{-1}$,

V_λ is the relative spectral sensitivity of the eye (luminous efficiency, see Figure 4.1-1).

(Actually, the color temperature of the source, since the adoption of the International Practical Temperature Scale of 1968, should be 2875 K and the luminous efficacy should be 673 lumen $watt^{-1}$. (108))

The total luminous flux is

$$\Phi_V = E_V A_{pc} \quad \text{lumens} \tag{4.5-4}$$

Finally, the luminous sensitivity is

$$S = \frac{i_{pc}}{\Phi_V Q} = \frac{\int E_\lambda R_\lambda d\lambda}{680 \int E_\lambda V_\lambda d\lambda} \quad \text{amp lumen}^{-1} \tag{4.5-5}$$

This calculation must be carried out for each different combination of source and sensor spectral curves. Eberhardt has published tables of source/sensor spectral matching factors (109). It is important to realize that the luminous sensitivity will change when a source different from the 2870 K lamp is used in calibrating the sensor. Table 4.5-1 (109) can be used for this purpose. For example, assume that the 2870 K luminous sensitivity of an S-25 image intensifier is known, and the device is to be used to view a sunlit scene. From the table the sensitivity to sunlight seen through two air masses is only 0.814 times the 2870 K sensitivity. Note that if any haze filters are used in the optical system, the values of Table 4.5-1 are not applicable. The effect of haze filters would to lower all values.

4.5.2.3 Photocathode Dark Current

One other parameter of importance is dark current which flows when there is no light input to the tube. The dark current or the shot noise associated with it may limit the low light level capability of a given sensor. The dark current of an S-20 image intensifier is usually negligible at room temperature. It increases with increasing temperature. Dark current becomes more severe as the red response of an S-20 or S-25 surface is extended. See Chapter 7 of (87). The dark current of an S-1 image intensifier is quite high compared to S-20 or S-25, and cooling is necessary if photoelectron shot noise limited performance is desired.

TABLE 4.5-1

CHANGE IN LUMINOUS SENSITIVITY WITH FLUX SOURCE R_L/R_L (CAL)
(2870°K CALIBRATING LAMP)

Sources	Photocathodes					
	S1	S4	S11	S17	S20	S25
Phosphors						
P1	0.497	0.996	1.063	1.141	0.576	0.347
P4	0.1062	2.100	1.955	1.793	1.138	0.670
P11	0.148	6.235	5.397	4.654	2.753	1.482
P20	0.0767	0.616	0.716	0.782	0.520	0.346
Lamps						
2870/2854 std	1.000	1.000	1.000	1.000	1.000	1.000
Fluorescent	0.1083	1.195	1.173	1.126	0.800	0.501
CIEA	1.0612	0.976	0.986	0.987	0.990	1.0233
Sun						
In space	0.410	2.638	2.169	2.078	1.428	0.955
+2 air masses	0.374	1.840	1.669	1.571	1.154	0.814
Day sky	0.378	3.665	2.763	3.403	1.681	1.287
Blackbodies						
6000°K	0.438	2.835	2.272	2.203	1.499	0.975
3000°K	0.945	1.084	1.062	1.057	1.013	0.967
2870°K	1.0373	1.022	1.013	1.014	1.0056	1.007
2854°K	1.0618	1.0079	1.0021	1.007	1.0089	1.015
2042°K	3.011	0.630	0.694	0.740	1.145	1.561

4.5.3 TV CAMERA TUBES

4.5.3.1 Devices

The optical image is formed upon the photosensitive surface of the TV camera tube (or pickup tube). Two types of photosensitive surfaces, photoemissive and photoconductive, are used. The "front end" of a camera tube with a photoemissive surface is much like an image intensifier. Photoelectrons are accelerated through an electric field and strike the target, or signal plate, where they are responsible for generating an electron image. This image, or signal, is integrated and stored for subsequent examination by the reading beam, each point in the image being interrogated sequentially,

once each frame (see Paragraph 4.2.2.2). The reading beam acts to restore the target to its unexposed condition. The variation in reading beam current required to do this is in proportion to the photon density at the photocathode. Typically, there is electron gain in the target, due to creation of secondary electrons or electron-hole pairs from incident high energy photoelectrons.

In the photoconductive TV camera tubes, the incoming photons cause an increase in conductivity which is a function of the photon density at each point in the optical image. That is, the photons generate an electron image directly at the target or signal plate. This electron image is integrated and stored for readout, as in the photoemissive type tube. Generally, electron gain in the target is not possible.

Just as these are two commonly used photosurfaces, there are also two commonly used methods of signal readout. The signal may be extracted directly from the signal plate by measuring the instantaneous current deposited by the reading beam, as shown in Figure 4.5-3a, c. As an alternative, a return beam readout can be employed. Return beam readout is based upon the fact that the reading beam electrons which are not required to restore the target to its unexposed condition are reflected from the target and returned toward the electron gun. Return beam readout is usually implemented so that the returning beam strikes dynodes and is thus amplified prior to readout. Figure 4.5-3b, d illustrates this principle of achieving electron gain.

Table 4.5-2 lists some of the more important TV camera tubes and their characteristics. The tubes are ranked approximately in order of increasing sensitivity. Note that there are various combinations of photosensitive surfaces and readout methods. Figure 4.5-4 contains the light transfer characteristics (light in versus signal out) of some of these tubes.

The vidicon tube has a spectral responsivity curve which covers the visible spectrum and is somewhat broader than that of the human eye. Peak responsivity values, for low values of signal current, are comparable to those of the S-20 photoemitters. The signal current of the vidicon is not linear with light level, but obeys the law,

$$i \propto \Phi^{\gamma} \qquad (4.5\text{-}6)$$

where

Φ is input flux,

γ is the slope of the signal versus flux curve on log-log paper.

Typical values of gamma range from 0.5 to 0.7. Thus, in effect, the vidicon becomes less sensitive at higher light levels. Target sensitivity can be controlled by varying the target bias voltage.

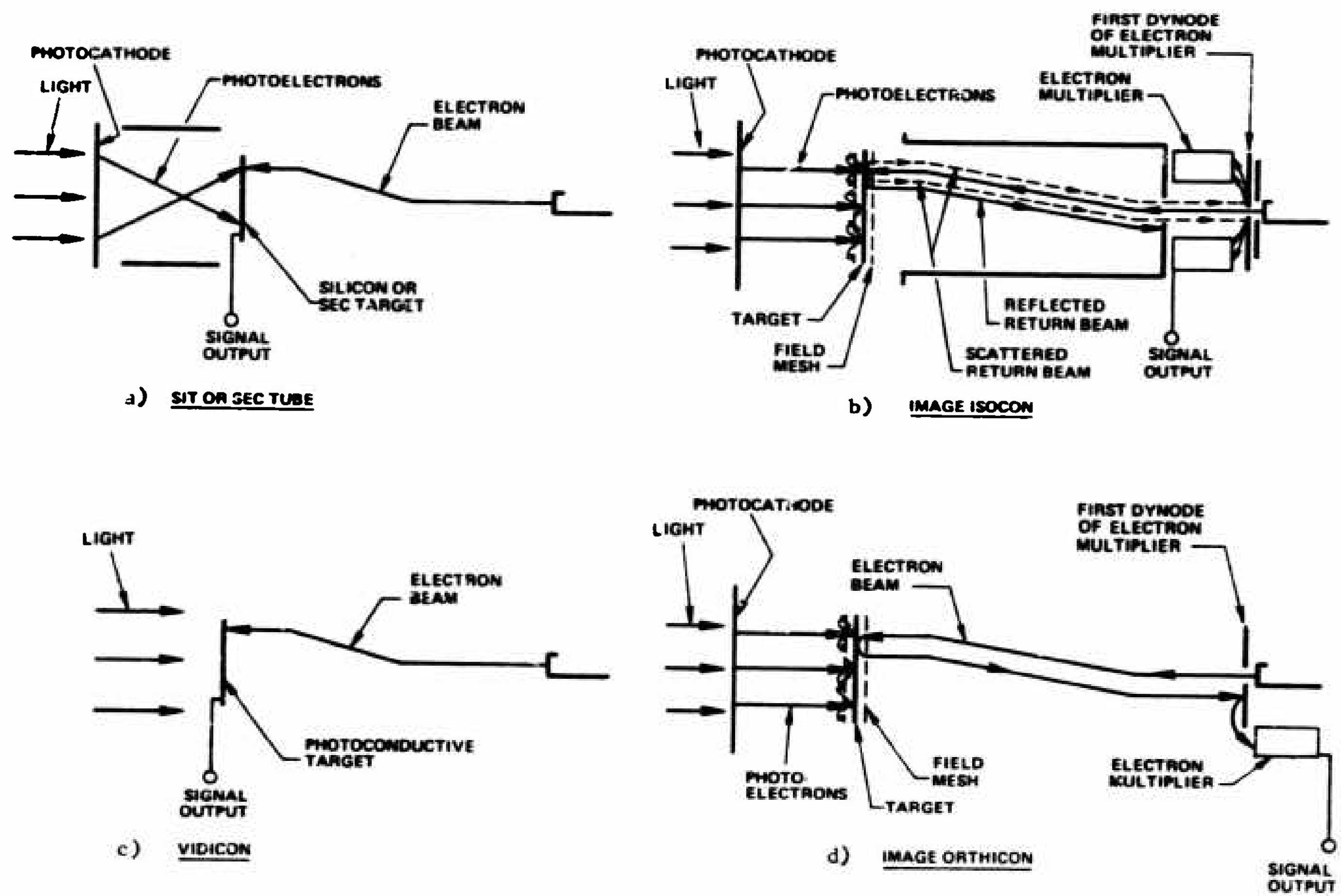


FIGURE 4.5-3. SCHEMATIC DIAGRAMS OF SOME TV CAMERA TUBES (64)

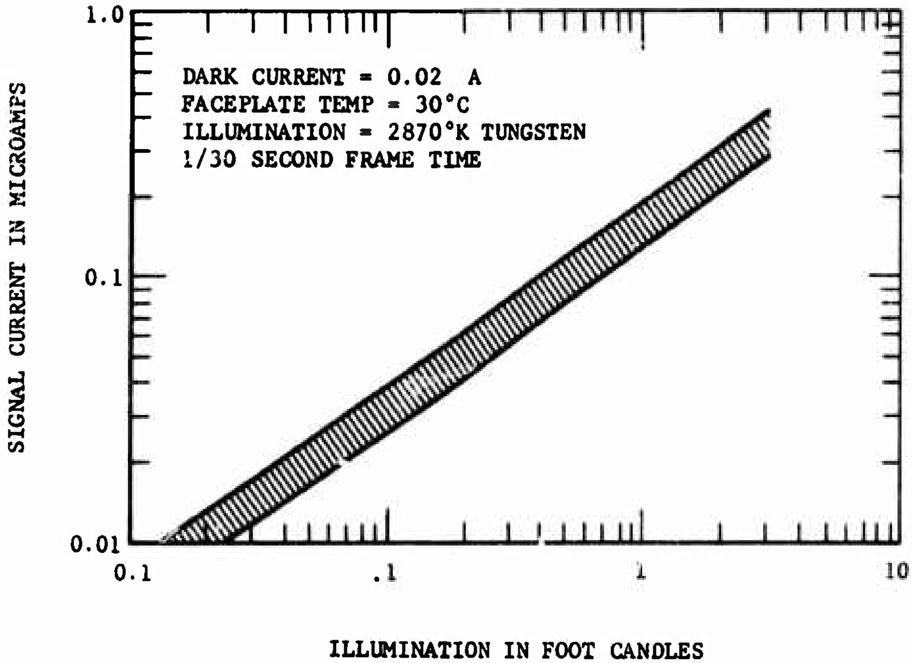
TABLE 4.5-2

TELEVISION CAMERA TUBE CHARACTERISTICS

Tube Type	Photosurface	Readout	Approximate Target Gain	Approximate Return Beam Gain
Vidicon	Photoconductor	Direct	1.0	N/A
Lead Oxide Vidicon	Photoconductor	Direct	1.0	N/A
Silicon Vidicon	Silicon Diode Array	Direct	1.0	N/A
Return Beam Vidicon	Photoconductor	Return Beam	1.0	1000
SEC Vidicon	Photoemissive	Direct	100	N/A
Image Orthicon	Photoemissive	Return Beam	4	1000
Image Isocon	Photoemissive	Return Beam	4	1000
Silicon EBIC (EBS or SIT)	Photoemissive	Direct	2000	N/A

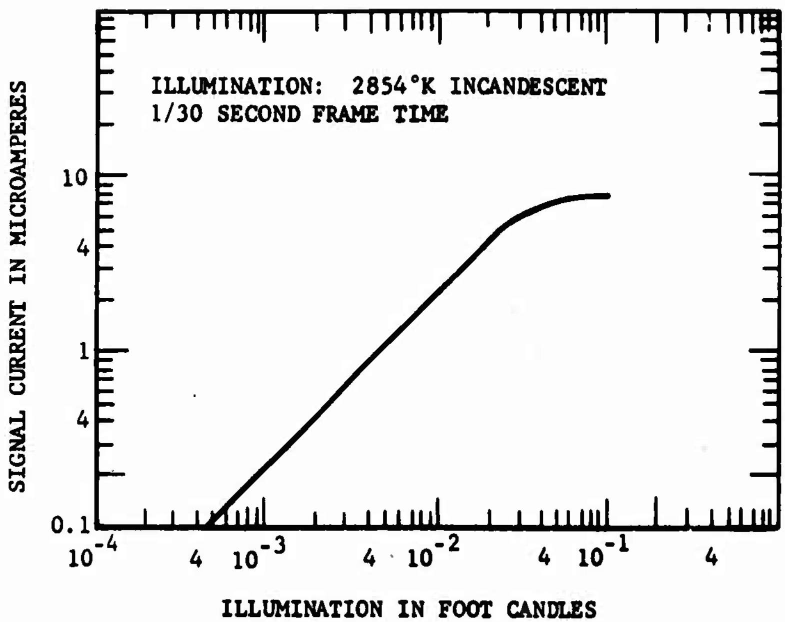
The lead oxide vidicon employs a lead oxide target in place of the antimony trisulfide target utilized in the original vidicon tubes. The spectral responsivity curve of the lead oxide vidicon also covers the visual spectrum, but is somewhat narrower than that of the vidicon. Peak responsivity is slightly higher, and the gamma is nearly unity so that signal current is directly proportional to input flux. This device is also known by its trade name, Plumbicon, when manufactured by Amperex.

The silicon vidicon uses an array of silicon diodes in place of the standard vidicon target. The spectral responsivity curve peaks in the red or near infrared and covers the spectrum from 0.4 to 1.0 micrometer. The peak spectral responsivity is higher than that of the vidicon with quantum efficiencies in excess of 50 percent being readily achieved. Unlike the standard vidicon, sensitivity control varying the target voltage is not practical in the silicon vidicon.



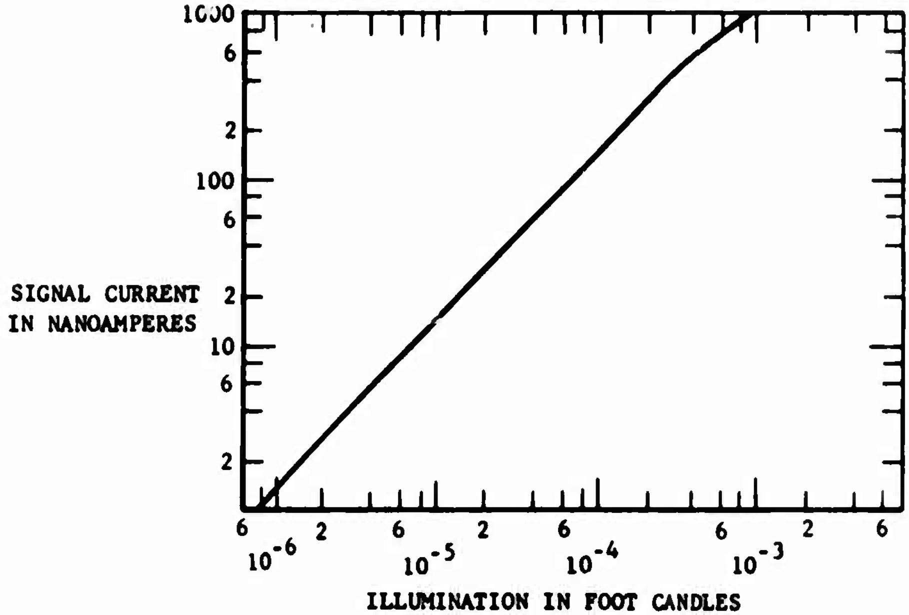
(a) VIDICON

FIGURE 4.5-4. TYPICAL LIGHT TRANSFER CHARACTERISTIC (γ) FOR THREE TUBE TYPES



(b) IMAGE ISOCON

PHOTOCATHODE VOLTAGE --- 10 KV
ILLUMINATION -- 2870°K TUNGSTEN
1/30 SECOND FRAME RATE



(c) ELECTRON BOMBARDMENT SILICON (EBS)

The return beam vidicon is a large target tube developed for its very high resolution capability. See Chapters 16, 17 and 18 of (100).

The SEC (Secondary Electron Conduction) vidicon employs a photoemissive surface identical to those used in image intensifiers. Photoelectrons are accelerated through an 8 KV electric field to strike a potassium chloride target, where a large number of secondary electrons are created. The signal is read from the target as in an ordinary vidicon. Target gain, and therefore sensitivity, can be controlled by varying the accelerating electric field. Gamma is near unity.

The image orthicon also employs a photoemissive surface. Photoelectrons are accelerated through a low (600 volt) field to strike a glass target, where a few secondary electrons are created. A return beam readout is utilized. The light signal transfer characteristic has two distinct regions. Below the "knee" of the curve, gamma is near unity, while above the knee the output signal changes very little with increased light input. The tubes can be safely operated from two to four times the irradiance level associated with the knee.

The image isocon is very similar to the image orthicon. The essential difference is in the manner that reading beam electrons are collected. In the image orthicon, both specularly reflected electrons and scattered electrons are collected for amplification and readout. The number of scattered electrons is everywhere proportional to accumulated charge density on the target, whereas specularly reflected electrons are greatest in number where there is no accumulated charge on the target. The image isocon uses only the scattered electrons, and as a consequence, the signal current is directly proportional to light flux. Image orthicon signal is the complement of this, so that the larger number of electrons in the beam signal is due to dark portions of the scene. Since shot noise is proportional to the square root of signal current, the dark portions of the image orthicon scene are more noisy than the dark portions of an image isocon scene. Thus the sensitivity of the image isocon is extended to lower light levels than the image orthicon. The light transfer characteristic is similar to that of the image orthicon.

The silicon EBIC (Electron Bombardment Induced Conductivity) is constructed much like the SEC vidicon. The essential difference is that the potassium chloride target is replaced with a silicon diode array target. This can be the same diode array as used in the silicon vidicon. In this case, the charge image is due to electrons rather than photons landing on the array, and a very large electron gain is achieved in the target. The light transfer characteristic is essentially linear, so that gamma is near unity. This device is known as an EBS tube when manufactured by Westinghouse and a SIT when manufactured by RCA.

4.5.3.2 Signal Gain and Sensitivity

The need for signal gain depends upon the light levels at which the sensor must operate. A typical vidicon produces an output signal of 150 to 300 nanoamperes when the faceplate illumination is one footcandle. This signal, in the case of the vidicon, is fed directly to the video preamplifier, where it competes with an equivalent input noise of 3 to 15 nanoamperes rms, depending on bandwidth and cost. With a photosurface illumination of one footcandle, a typical vidicon camera will meet its full set of specifications. For a T/1 (see Paragraph 4.4) optical system, this means that about 12 footcandle must be incident upon a 25 percent reflecting scene. For lower values of incident illumination or slower (higher T/no.) optics, the rated value of target signal current will not be generated.

Lower values of target signal current result in a lower value of signal-to-noise ratio, as the sensor is being read out into a preamplifier of constant noise current. The lower signal-to-noise ratio results in loss of ability to distinguish fine scene detail, as well as loss of ability to distinguish shades of grey. As the signal-to-noise ratio goes to lower and lower values, the quality of the picture deteriorates until such a point that the imagery becomes useless.

Thus, in many cases it is necessary to provide amplification of the photoelectron signal prior to its being read out into the (noisy) preamplifier.

If a noise-free electron gain of 1000 can be realized prior to signal readout, then operation can be extended to scene illumination values 1000 times less than above. However in fact, the electron gain of practical devices is not entirely noise-free, but for a first approximation certain types of electron gain can be considered nearly so. In particular, gain provided in an image intensifier, or an SEC or SiEBIR target, is nearly ideal. Tubes such as the image orthicon, in which return beam readout is used, contribute shot noise due to the readout beam current, and thus do not approach the ideal as closely.

If even more gain is required, one or more stages of image intensifier may be coupled to any of the tubes which have been discussed. The limit on useful gain is reached when the signal-to-noise ratio is solely dependent upon photoelectron shot noise, that is, the noise inherent in the signal. The combination of a single stage intensifier and a silicon EBIC tube is photoelectron shot noise limited for all practical purposes. (See Chapter 22 of (100).) The penalty for adding intensifier stages is that limiting resolution is reduced due to the MTF of the additional components in the chain.

Another camera tube property which must be considered is the ability to image moving or changing scenes. The readout beam is unable to completely neutralize the accumulated charge on the target in a typical TV frame time.

The residual signal which is left on the target is referred to as lag. Lag is dependent upon tube type, and within tube type, upon light level. Vidicons are the most "laggy" of the tubes discussed, becoming particularly laggy at lower light levels. One of the reasons for the development of the lead oxide vidicon was to reduce lag. The silicon EBIR and SEC vidicon are the least laggy of the tubes discussed.

Other important properties which often must be considered are the ability to handle large intrascene dynamic range, and to withstand overloads due to bright sources in the field of view. Susceptibility to microphonism and the effect of temperature upon performance also vary with tube type.

In development are arrays of solid state image sensors which are self-scanning. They are capable of providing a video output without a reading electron beam. It is expected that these sensors will offer a much broader range of application than existing TV camera tubes. (110)

4.5.4 FLIR SENSORS

4.5.4.1 FLIR Implementation

In a FLIR sensor, an image of the infrared scene is formed by an objective lens. An array of infrared detectors is located in the focal plane of this lens. The image of the scene is caused to scan across the detector array, as shown in Figure 4.5-5. As the scene is swept past the array, a time-varying signal is generated by each detector in response to the differing values of radiance in neighboring scene elements. The output from each detector is coupled to its own preamplifier. After amplification, the large number of parallel channel signals are processed by a multiplexer, which combines all of the information into a single channel for display on a cathode ray tube. The resultant imagery is very much like television imagery in appearance, although tones are a function of temperature or emissivity differences rather than reflectance differences.

An important dissimilarity between a FLIR sensor and a TV camera is that each element of the FLIR scene is examined only once during a frame. The period of examination is equal to the dwell time, i.e., the time that it takes for a point in the scene to scan across a detector element. By contrast, the entire field of view is continually seen by a TV camera, so that photon flux is integrated for the full frame time.

This is not altogether undesirable for the FLIR set. Reflectivities vary greatly in the visible spectrum, so that large contrasts are available to the TV sensor. In the FLIR spectra, emissivity and temperature differences are small, so that the "signal" consists of small radiance differences superimposed upon a very large background radiance. Barhydt has pointed out that "even if it were possible to sensitise photographic film for use in the intermediate infrared region, a photographer would be faced with a

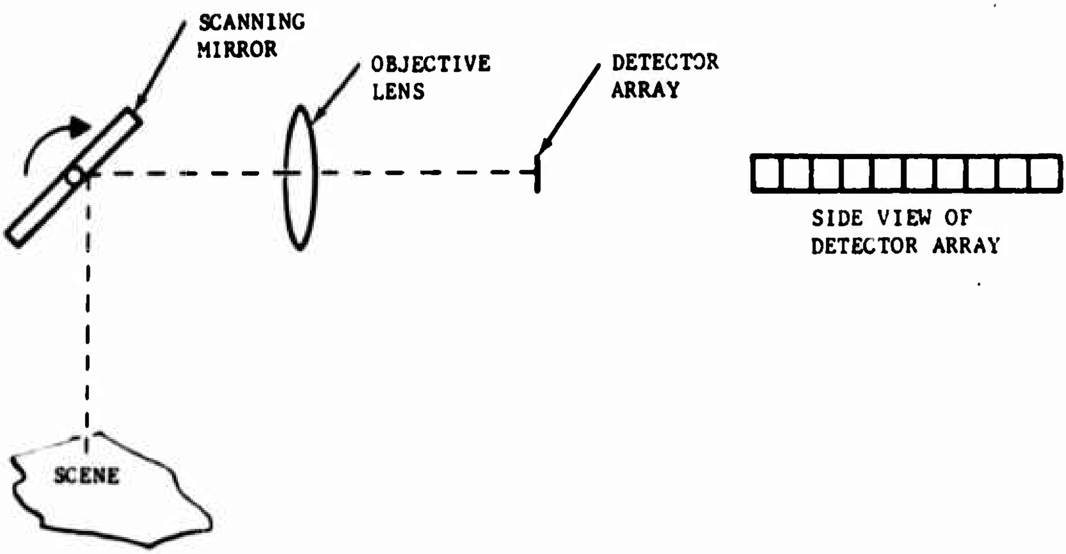


FIGURE 4.5-5. SIMPLIFIED SCHEMATIC OF FLIR SENSOR

problem analagous to that of visually photographing a white sheet of paper attached to a freshly painted white wall." (60) Hall (111) has shown that for operation beyond about 2.5μm, the background flux is so great that an integrating sensor such as an IR TV camera would saturate on background, and therefore would not be able to handle the small flux differences which constitute signal. For this reason, IR sensitive TV cameras fail to compare in performance to the less efficient FLIR sets. Hall shows that a camera tube can give signal equal to noise only for contrasts above 0.2 percent to 1 percent at best, while a typical FLIR sensitive to 12μm approaches 0.001 percent with a 300 K background.

There are several methods of generating the FLIR scan. Optical elements may be scanned ahead of the objective lens as shown in Figure 4.5-5. This is known as object plane scanning. Or, the scanning may take place behind the objective lens, close to the image plane. This latter configuration usually requires less volume to mechanize.

The detector array may be contiguous, as shown in Figure 4.5-5, or alternate rows of detectors may be left out and alternate fields interlaced as in standard television. Interlacing cuts down on the number of detector/amplifier channels required to cover a given total field of view at the sacrifice of sensitivity.

To achieve the sensitivity required for high resolution systems operating at or near television frame rates, it is necessary to cool the detector elements to cryogenic temperatures, typically 77 K or lower. Well designed FLIR sets are capable of operating in a background limited performance (BLIP) condition, which means that the only significant source of noise is the photon induced shot noise due to the background flux. It is therefore desirable to limit background flux to that which comes from the viewed scene. To do this, it is necessary to include a "cold shield" which prevents extraneous flux from the FLIR housing, etc., from reaching the detector array.

If it is desired to convert the signals of the many detector channels into a single, TV-like video signal (and it usually is), a step called multiplexing is included in the signal processing chain. Two types of multiplexing are employed with FLIR sets. Electronic multiplexing involves sampling the output of each detector/amplifier channel at a high rate, so that at least two samples are obtained from each channel per dwell time. Dwell time, it will be remembered, is the time it takes for a point in the scene to traverse a detector element. Electronic multiplexer bandwidths run in the tens of megahertz. Because of the multiplexing format, a special scan pattern may be required on the CRT display, so that conventional TV scanning standards may not be compatible.

The other commonly used form is called electro-optical multiplexing. The output from each detector/amplifier channel is fed to a light emitting

diode (LED). The LED array is arranged to correspond geometrically to the detector array, and is optically scanned in synchronism with it. In the simplest of FLIR systems, this LED array is viewed directly by the eye; and if the field rate is sufficiently high, a flicker-free scene image will be seen. Where a remote view is required, the LED array is imaged onto a TV camera tube; and the image is optically scanned across the tube faceplate once each field. The TV camera then converts the signal to a standard video signal which can be displayed on a conventional TV monitor. (Even though the TV camera tube is capable of integrating the signal for the full frame period, no integration takes place because each element is exposed only once per frame due to the LED scanning.)

4.5.4.2 Resolution and MTF

The finite size of the individual detector element sets a limit on the angular resolution of the FLIR sensor. In the past, it was common to equate the detector instantaneous field of view of the FLIR sets to its resolution. That is, if the individual detector element subtended 1 milliradian, the FLIR set was referred to as a 1 milliradian system. In fact, however, the resolution of the FLIR set may not approach the limit set by the detector instantaneous field. The overall system response is the convolution of the line spread functions of the system components, including the objective optics, the detector, the electronic amplifiers, the multiplexer, and the display. The system MTF (see Paragraph 3.3) is the product of the MTF's of each of these components. MTF is the recommended measure of system resolution. (7)

The MTF curves for objective optics were given in Figures 4.4-14, 15 and 16 of this report. Those curves are plotted in values of normalized frequency, ν/ν_o, where ν is in line pairs/space unit, and ν_o is the cutoff frequency in line pairs/space unit.

The cutoff frequency is given by

$$\nu_o = \frac{10^3}{\lambda F} \text{ line pairs/mm} \qquad (4.5\text{-}7)$$

where

λ is wavelength in μm,

F is focal ratio.

In angular resolution units, the cutoff frequency is

$$\psi_o = \frac{D}{\lambda} \text{ line pairs/mr} \qquad (4.5\text{-}8)$$

where

D is objective diameter, millimeters,

λ is wavelength in μm.

Since the FLIR wavelengths are from 5 to 25 times longer than visible wavelengths, the resolution limits are more severely restricted by objective lens performance. A FLIR system with fine angular resolution will require a large aperture, per Equation (4.5-8). For example, if a resolution of 10 line pairs per milliradian is desired and the FLIR set works at 10 micrometers, the aperture diameter must be greater than 100 mm if the system is to have any response at the required frequency. For a diffraction limited MTF of 50 percent at the required frequency, the normalized frequency must be 0.5 of the cutoff frequency (see Figure 4.4-14). Thus, ψ_o must be equal to ψ/0.4 or 10/0.4 or 25 line pairs/mr, which requires the objective diameter to be 250 mm.

The MTF due to a rectangular detector is given by

$$MTF = \frac{\sin (\pi \psi \theta_d)}{\pi \psi \theta_d} \qquad (4.5\text{-}9)$$

where

ψ is angular frequency, line pairs/mr,

θ_d is instantaneous field of view of detector in scan direction in mr.

This function is plotted in Figure 4.5-6. The MTF goes to zero when the spatial frequency is just equal to the detector instantaneous field of view. Resolution beyond this point is spurious and actually detracts from image quality (Paragraph 4.7.3.2). The system should be designed so that the overall MTF cuts off at a value $\psi \theta_d$ equal to or less than unity to avoid spurious resolution effects.

The MTF due to the electronic amplifier can be made unity for the spatial frequencies of interest simply by making the electrical frequency response function flat to the required bandwidth (Paragraph 4.7.3.1). Note however, that there will always be a phase shift associated with electronic signal processing.

The MTF due to the multiplexer is a function of the type of multiplexing employed. By maintaining a flat frequency response out to the highest required frequency, the MTF of an electronic multiplexer can be unity. With electro-optical multiplexing, two additional MTF contributors are added to the system. Because each LED has a finite size rather than being

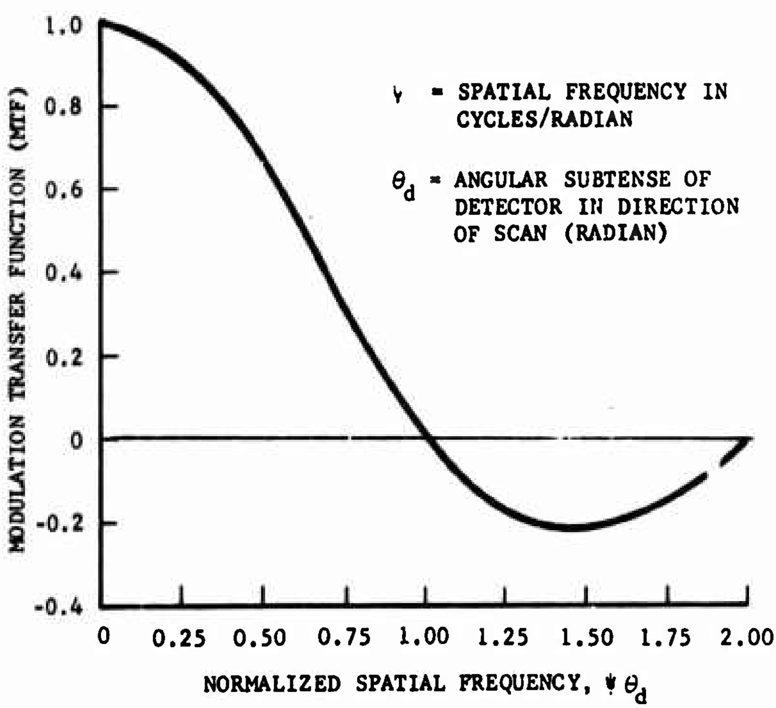


FIGURE 4.5-6. MODULATION TRANSFER FUNCTION FOR A RECTANGULAR DETECTOR SCANNING APERTURE

a point, the LED array contributes an MTF. For a rectangular LED, the MTF equation is the same as that for the detector, given by Equation (4.5-9). However, the MTF for the LED array usually is made better than that for the detector by making the LED narrower than the detector in the direction of scan.

The MTF of the camera tube and electronics must also be included in the system MTF.

Finally, the MTF of the display has to be taken into account in evaluating total system MTF.

The following rule of thumb can be used to roughly evaluate FLIR sensor MTF. The line spread function (LSF) of a typical FLIR system can be approximated by (7).

$$\mathrm{LSF} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp -\frac{1}{2}(\zeta/\sigma)^2 \qquad (4.5\text{-}10)$$

where

ζ is an angular variable for dimension in scan direction, mr,

σ is the standard deviation of the LSF, mr.

A typical range is given in (7), as

$0.70\ \theta_d \leq \sigma \leq 0.4\ \theta_d$.

where θ_d is the detector instantaneous field of view in the scan direction, mr. The MTF associated with the above line spread function is

$$\mathrm{MTF} = \exp -\frac{1}{2}(2\pi\sigma\psi)^2 \qquad (4.5\text{-}11)$$

where ψ is spatial frequency, line pairs/mr. Those FLIR sets with values of σ close to $0.4\ \theta_d$ more nearly approach the limit set by the detector instantaneous field of view. Thus, the MTF of other contributors must be high, which implies a large aperture as a beginning.

One historical objection to equating detector instantaneous field of view to system angular resolution is that a high signal-to-noise ratio is necessary to approach the "limiting resolution." (See Paragraph 3.3.) That is, assuming that the limiting resolution could be achieved against small targets with large temperature differences, nothing is known of the system's utility against small targets with small temperature differences. Likewise,

it should be realized that MTF is valid as the sole measure of system resolution only when the signal-to-noise ratio is relatively high. For low values of signal-to-noise ratio, system thermal sensitivity and MTF must be considered together, as discussed below.

4.5.4.3 Minimum Resoluable Temperature

In the past, it was common to evaluate system thermal sensivity in terms of noise equivalent temperature difference (NETD, NEΔT, or just NET). NETD is, by definition, the temperature difference between two objects which will produce a peak signal output equal to the rms noise. The objects used in measuring NETD are large compared to the detector instantaneous field of view, and the signal-to-noise ratio is measured at the output of a detector/amplifier channel. This number is readily calculated from known sensor parameters (see, for example, (60) or (112)) and is also conveniently measured. However, it is not a good measure of the system response to small targets differing by small temperature increments. Just as detector instantaneous field describes only the performance for small targets with large temperature differences, NETD describes only the performance for large targets with small temperature differences. What is needed is a measure of thermal sensitivity for targets of various sizes.

This need is met by Minimum Resoluable Temperature Difference (MRT) (112). The operational definition of MRT (2) is "the lowest equivalent blackbody thermal difference between target and its background at which a spatial frequency ν can be resolved by an observer with unlimited viewing time. The target is four-bar, square wave pattern with a bar aspect ratio of 7 to 1." Note that the MRT is measured by a trained observer viewing the display so that total system performance is measured.

Analytically, MRT is related to NETD and MTF. See (112), also (113) for a slightly different treatment. MRT is calculated by calculating the minimum signal which will produce the required signal-to-noise ratio in the area of the displayed bar pattern. As the bar dimensions increase, the eye is able to integrate flux over the greater area and therefore less flux difference is required for pattern recognition. Normalized MRT is plotted as a function of normalized spatial frequency in Figure 4.5-7, from (7).

Specific equations for MRT are given in Paragraph 4.7.2.7.

The third important FLIR system specification is its signal transfer function (STF) which is defined as "the relationship between large area differential temperature into the system and differential brightness at the display. It is recommended that it be measured at least at both maximum and minimum gain, each at various reproducible brightness settings to determine the total system dynamic range." (7) Figure 4.5-8 is representative of the results of such a set of measurements.

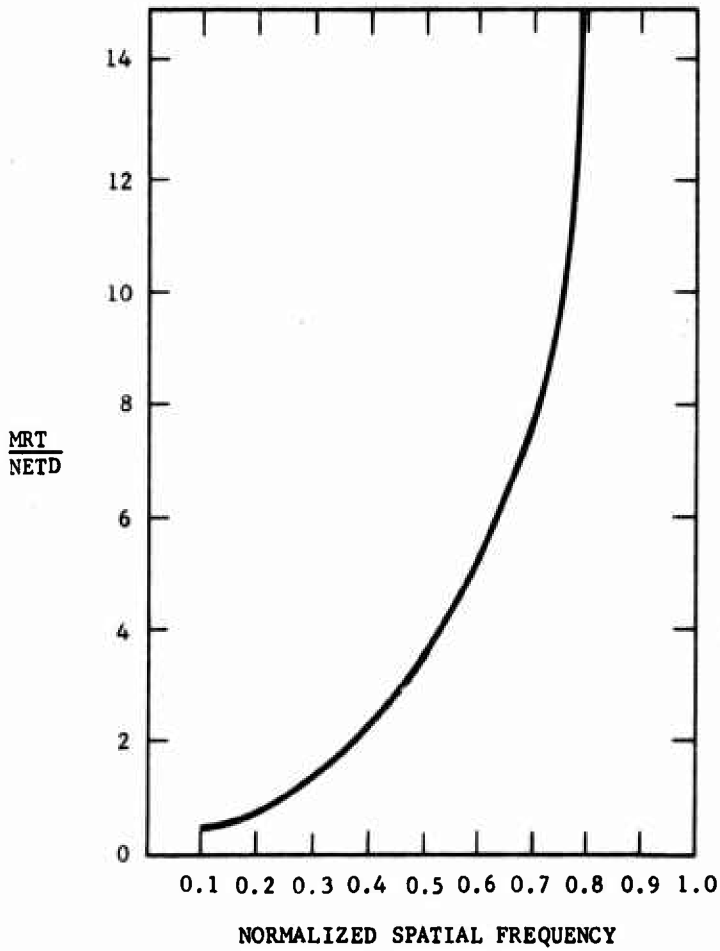


FIGURE 4.5-7. NORMALIZED MRT VERSUS NORMALIZED SPATIAL FREQUENCY (7)

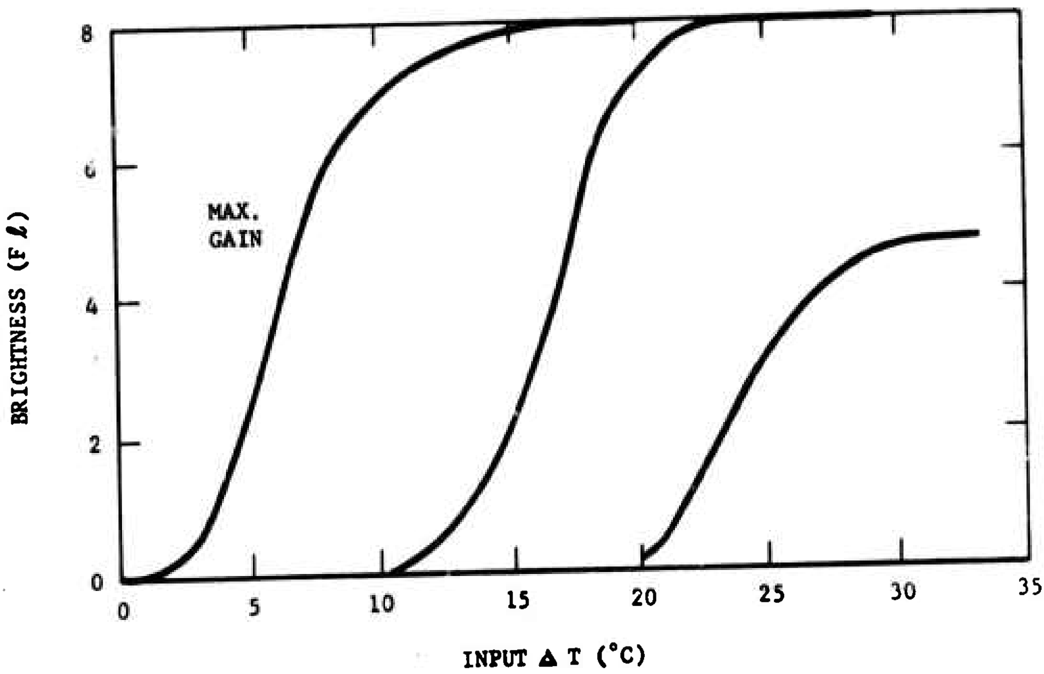


FIGURE 4.5-8. SIGNAL TRANSFER FUNCTION (7)
(CURVES FOR 3 GAIN SETTINGS)

4.6 Image Motion

Section 4.6 describes the effects of relative image motion upon imaging system MTF. Several types of image motion are discussed along with means of stabilizing the image in order to preserve system MTF.

4.6.1 EFFECTS OF IMAGE MOTION

In still photography, movement of the image during the exposure period results in a blurred picture. The same phenomenon occurs in a TV camera, since each frame (during which time signal is stored for readout) is an exposure period. Therefore, if a point is to be observed, and its optical image moves on the TV photosurface during a frame, the displayed image will be blurred.

Image motion has several causes. The sensor may be "panned" in a search pattern. If the panning rate is too fast, the picture becomes blurred beyond recognition. Or the sensor may be on a moving vehicle, and the sensor may be aimed at some fixed angle, in which case the scene moves past the sensor. If the sensor is located on a moving vehicle or is on an otherwise unstable platform, the line of sight may jitter about its nominal position. Atmospheric turbulence will also cause the image to dance about, as noted in Paragraph 4.3.3.4.

The effect of image motion is most severe in high resolution systems. In most cases these are high magnification, narrow field of view systems. The experience of trying to view through hand-held 20 power binoculars (as opposed to 7 power) is a good example.

The effect of image motion on viewing system performance can be evaluated by means of the modulation transfer function due to image motion. The MTF's of three important types of image motion are shown in Figure 4.6-1 (101 and 102). For the random motion case, it is assumed that the image jitters about its nominal position with an RMS amplitude of Λ_{RMS} milliradians. It is further assumed that the temporal frequency of the image jitter is greater than the inverse of the frame time (30 Hz in the case of standard TV systems). When viewing TV imagery, there is evidence that the eye integrates over several frames (Paragraph 4.1.1.4.2) and that the effect of image blurring is identical for all frequencies above about 10 Hz. (103). At lower frequencies, the eye is able to follow the image motion to some extent and the degradation is not so severe as predicted by the curves of Figure 4.6-1.

While the normalized curves of Figure 4.6-1 are labeled in terms of spatial frequency in line pairs per milliradian, any other set of compatible scales can be used. Thus ψ can be in line pairs/millimeter (which is ν) and Λ in

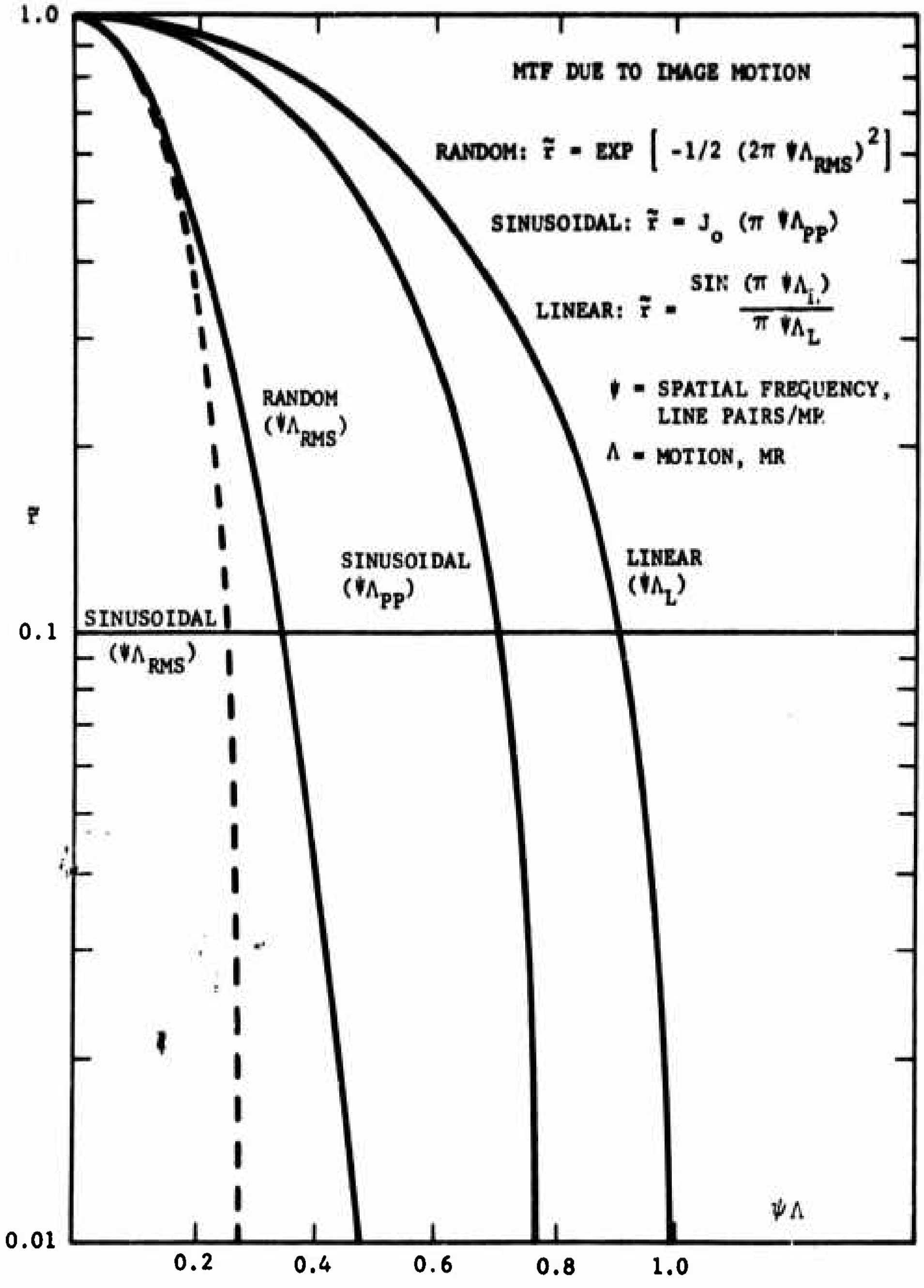


FIGURE 4.6-1. MODULATION TRANSFER FUNCTION DUE TO IMAGE MOTION

millimeters, or ψ in TV lines/frame (which is N_{TV}) and Λ in fractional frame height.

Two curves of sinusoidal image motion are plotted in Figure 4.6-1, one plotted in terms of RMS amplitude, one in peak to peak amplitude. A given RMS value of sinusoidal motio is seen to be more severe than a similar RMS value of random motion. The sinusoidal motion MTF curves again assume that the motion frequency is greater than the frame time or observer's integration time. More properly at least a few cycles of motion should occur during the frame time for Figure 4.6-1 to apply.(104).

Vibration-induced motion, such as on an aircraft, is often considered to be sinusoidal motion. In many cases, however, the amplitude is not constant with time, and the motion can best be described by "narrow band" noise, or random amplitude motion.

The final curve of Figure 4.6-1 is the MTF due to linear motion during the exposure period. Such motion results from panning or operation from a moving vehicle.

The effect of motion on limiting resolution may be assessed with the aid of the normalized curves shown in Figure 4.6-2. Asymptotes are shown for the three types of motion considered in Figure 4.6-1. The curves may be interpreted as follows: For values of motion, Λ, which are small compared to the sensor static resolution element, $1/\psi_0$, the effect of motion is minimal, and the system resolution is nearly equal to the sensor static resolution. As the relative motion increases, system resolution degrades until such a point that the system resolution becomes solely a function of image motion. At this point the system designer should consider image motion compensation, sightline stabilization, or settle for a lower resolution sensor.

Also shown in Figure 4.6-2 is a curve of experimentally measured resolution, when sinusoidal motion was added to an image viewed with a TV system (103). In this measurement, the motion degraded resolution was worse than would be predicted by the asymptote. This result agrees with earlier published measurements for a photographic system (105).

In the case of some TV camera tubes, the performance with image motion can be substantially worse than predicted by the MTF equations, due to lag in the camera tube (see Paragraph 4.5.3). This is especially true when the tube is operated at lower than optimum light levels. When any doubt exists, both static and dynamic (with motion) resolution should be specified.

FLIR systems do not store or integrate the image signal over the frame period, but rather each "element of the scene" is sampled only once per frame. In this case, the effect of image motion is not nearly so severe, if each

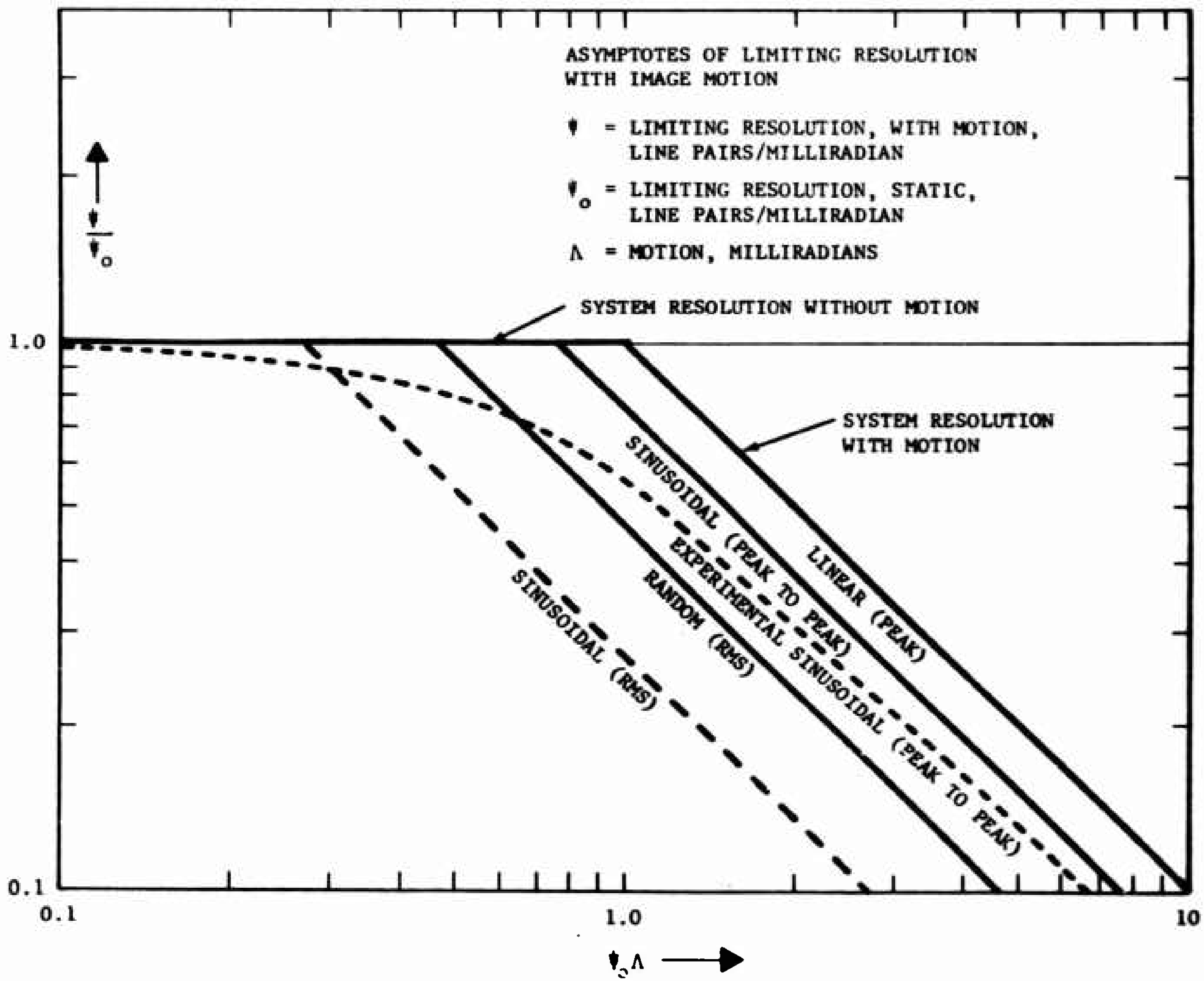


FIGURE 4.6-2. ASYMPTOTES OF LIMITING RESOLUTION WITH IMAGE MOTION

frame is examined separately. Long objects which lie in the direction of motion may be lengthened or shortened, while lines that lie across the direction of motion will be staggered in an interlaced system. (106). When it is considered that an observer viewing a live FLIR image uses several frames in making his judgments, he will then be presented with several images displaced from one another rather than the blurred image of a TV system. This superposition of misregistered images will also degrade MTF and resolution. No analyses or experimental data are available at this time.

4.6.2 STABILIZATION TECHNIQUES

Image motion which is a result of sensor vibration or motion can be reduced or compensated in various ways. The most straighforward method is to stabilize the sensor in inertial space. In the simplest conception, the sensor is mounted in gimbals, and decoupled from the moving platform by minimizing friction. The inertia of the sensor tends to stabilize its sightline. When a greater degree of stabilization is required, sensor motion is detected by gyros and signals are fed back to torque motors which act to oppose the sensor motion.

A more sophisticated and more versatile approach stabilizes only the sightline of the sensor (and possibly other optical and electro-optical equipments), rather than stabilizing the sensor itself. In this approach, an optical element (usually a mirror) is stabilized so that the sightline is decoupled from motions on the platform and the sensors mounted on it. Finer stabilization, plus greater search field coverage in a smaller package, are obtainable with this approach.

If an image intensifier is employed in the sensor ahead of any integrating or storage media, image stabilization may be accomplished by applying a varying magnetic field to the image intensifier in response to gyro inputs. This magnetic field deflects the photoelectron beam in the intensifier in a manner that the electron image is stabilized on the phosphor screen of the intensifier.

4.7 System Analysis

Section 4.7 is an introduction to system analysis, the analytical process in which component parameters are combined in a manner to define a system with suitable imaging properties. An overview and specification philosophy section are also included. The system analysis presented are elementary and fairly typical of the product that a system engineer might obtain as a first effort in defining system performance capabilities. Even though the level of the material in Section 4.7 is introductory, it is expected that the novice in imaging system analysis will have to study and reread the material including portions of this document which are referenced. System requirements are developed from observer requirements. The various types of sensors are discussed in terms of their sensitivity and image quality (MTF, MRT) properties. Processing of the sensor output signal is also discussed.

4.7.1 OVERVIEW

The system designer must interrelate and trade-off the processes involved with the image information flow from mission parameters through component and system performance parameters to a measure of human success (such as the probability of detection of a target). He must include in this process the allocation of performance parameters and their tolerances to provide the optimum solution for the cost and schedule constraints imposed upon the system development (Section 2.2).

The system analysis generally is accomplished in two phases. The first phase is concerned with the determination of all boundaries and constraints. The constraints will include mission requirements, interfaces, environments, costs, schedules, and type of procurement. The second phase is concerned with determining the interdependencies and interactions of components in the system and optimizing the distribution of performance requirements. He will do this in a manner which results in a balanced system; that is components will be selected in such a manner that the required or available performance, including observer limitation, is achieved without drastically overspecifying a particular component. If an observer is to be required to use a 4-inch display then it makes little sense to have an ultra-high resolution sensor.

4.7.2 SYSTEM DESIGN CONSIDERATIONS

The purpose of this section is to tie together the concepts which have been introduced, and to illustrate how these concepts might be applied

to an EO imaging problem. The order and rationale of the approach is not necessarily that which might be followed in every situation, but an attempt has been made to examine the major aspects of the problem. Certainly more sophistication and specialization is required for each individual problem than can be presented here.

It is important to realize that while the equations which are presented subsequently may give an illusion of mathematical accuracy, they rest upon a number of approximations and simplifications. Therefore the results of computations are best used to compare systems and to evaluate the effect of parameter value changes, rather than to predict system performance with absolute certainty.

Initial specification of the real time imaging system begins at the observer, and works back through the display to the sensor. The first consideration is apparent magnification, followed by resolution and sensitivity.

4.7.2.1 Magnification Requirements

To be readily detectable, the displayed image of a target must subtend between 12 and 20 minutes of arc (3.5 and 5.8 milliradians) in its maximum dimension to the observer. (Paragraph 4.1.2). If the target has a maximum dimension D_T and it is to be viewed at a range r, then its angular subtense is

$$\theta_T = \frac{10^3 D_T}{r} \text{ milliradians} \tag{4.7-1}$$

The apparent magnification which is required is

$$M = \frac{\theta_e}{\theta_T} \tag{4.7-2}$$

where $3.5 \text{ mr} < \theta_e < 5.8 \text{ mr}$. For example, if the target subtense θ_T is 1 mr, the required magnification is between 3.5 and 5.8 power.

The apparent magnification of the imaging system is given by

$$M = \frac{\beta}{q} \text{ or equivalently } M = \frac{\beta_T}{\theta_T} \tag{4.7-3}$$

where

β is the angle subtended by the display height at the viewers eye, mr,

q is the vertical field of view of the sensor, mr.

$_T$ is the angle subtended by the displayed target

θ_T is the angle subtended by the target with respect to the observer (Figure 4.3-3).

Normally, the viewer should sit so that his eye is at a distance between 3 and 4 times the picture height from the display. (Paragraph 4.1.2.1.4).

For these standard viewing conditions, the minimum display angular subtent, β_{min}, should fall in the range

$$\frac{1000}{3} > \beta_{min} > \frac{1000}{4} \text{ milliradians} \quad (4.7\text{-}4)$$

From this and (Equation 4.7-3) the maximum sensor field of view should fall in the range

$$\frac{1000}{3M} > q_{max} > \frac{1000}{4M} \text{ milliradians} \quad (4.7\text{-}5)$$

Note that field of view and magnification are inversely proportional. Using the extreme values of θ_e from (Equation 4.7-2)

$$95\,\theta_t > q_{max} > 43\,\theta_t \quad (4.7\text{-}6)$$

where q_{max} and θ_t are in milliradians

or

$$.023 > \frac{\theta_t}{q_{max}} > .015 \quad (4.7\text{-}7)$$

This says that the target to be readily detectable, should occupy a minimum of 1 to 2% of the sensor field of view. For a standard 525 line system, the target image will occupy 5 to 11 active scan lines. The higher number if preferred. There is nothing wrong with displaying a larger image, except that field of view is sacrificed. The field of view should be chosen as large as possible to insure a high probability of the target being in the field, while at the same time satisfying the minimum requirements of (Equation 4.7-7).

The field of view is determined by the focal length and image plane height (effective sensor size),

$$q = 2\tan^{-1}\frac{d}{2f} \approx \frac{10^3\,d}{f} \text{ milliradians (total field)} \quad (4.7\text{-}8)$$

where

d is sensor height at the image plane, mm,

f is effective focal length, mm.

If a TV camera tube or image intensifier is used, there are certain standard photosurface diameters available such as 16, 25, 40 and 80 mm. For TV usage, a 4:3 rectangle, or sometimes a square, is inscribed in this circle. FLIR detector array dimensions are usually limited by technology.

4.7.2.2 Resolution Requirements

The system resolution requirement is based upon the particular task which must be accomplished. The Johnson criteria were discussed in Section 4.1.2 and are repeated in Table 4.7-1.

TABLE 4.7-1. RESOLUTION REQUIRED FOR VISUAL TASK

Task	Resolution, ν_T (line pair/minimum target dimension)
Detection	1.0 ± 0.25
Orientation	1.4 ± 0.35
Recognition	4.0 ± 0.8
Identification	6.4 ± 1.5

To recognize a target, for example, 4 line pairs must be resolved on the minimum target dimension. This reckoning of resolution must be made with the same modulation that the target image is expected to have, so that inherent target contrast and atmospheric contrast reduction must be taken into account.

The system resolution required to perform a given task is

$$\psi = \frac{\nu_T}{\theta_{min}} \quad \text{line pairs/mr} \qquad (4.7\text{-}9)$$

where

ν_T is the appropriate value from Table 4.7-1, line pairs/target,

θ_{min} is the angular subtense of the minimum target dimension, mr/target.

The targets used to generate the above data had fairly modest aspect ratios, and it is apparent that the modeling breaks down when trying to calculate performance against a target of long aspect ratio, such as the beam view of a ship.

Acceptable results can be obtained in the prediction of observer performance by transforming the Johnson model (Table 4.7-1) to an area model of the target. (See Paragraph 4.1.2.2.1). The basis for this extension is that simple, uniform objects of equal area are equally visible and detectable. The transformation of models is apparently valid for simple targets with aspect ratios up to 45:1 (61). The extended model should be confirmed by test before its validity is totally accepted. Some tests have been performed by Rosell and Willson (41).

If an area model is used, the resolution cell is a square with dimensions of a TV line (1/2 of an optical cycle) per side instead of an optical line pair. In general a specific number of resolution cells can be associated with each of the tasks of detection, orientation, recognition, and identification. The required system resolution is then calculated in the following manner. Assume that the target solid angular subtense is Ω_T. An element is a resolved TV line, or half a line pair, so that the required resolution is

in general,

$$\psi = \frac{\sqrt{N_n}}{2\sqrt{\Omega_T}} \text{ line pairs/milliradian} \tag{4.7-10}$$

where:

N_n is the appropriate value for the number of resolution elements for a specific classification task

Ω_T is the target area subtense, 10^{-6} sr or $(mr)^2$

The relationship of Equation (4.7-10) may be used in lieu of Equation (4.7-9) when so indicated.

4.7.2.3 Viewing System Performance at High Signal Levels

Once the required value of resolution is found from either Equation (4.7-9) or Equation (4.7-10), the performance of the viewing system is calculated as follows. The modulation on the display, at the required value of resolution, must equal or exceed that required by the eye. If it can be assumed that the system signal transfer function is linear, that is, if the display incremental brightness is directly proportional to input incremental flux, then

$$m_R \overset{\sqcap}{r}_{sys} \geq m_e \tag{4.7-11}$$

where

- m_R is the apparent modulation of the target, at the required spatial frequency,

- $\overset{\sqcap}{r}_{sys}$ is the square wave response of the viewing system, at the required spatial frequency

- m_e is the modulation on the display, required by the eye for detection of a target at the required spatial frequency. (Note the angular spatial frequency of the target with respect to the observer is M times greater than that displayed.

Real systems may not be linear, in fact linearity of the signal transfer function may not be desirable, but it is usually found convenient to analyze the system as if it were linear.

The required value of modulation presented to the eye is given by the demand modulation function (DMF) which may also be known as the eye demand curve. The caution at the beginning of Paragraph 4.7.2, that mathematical statements and data may imply an accuracy beyond that which exists, is particularly true when it is the arena of observer requirements in which one is involved. The ambiguities in defining the "correct" DMF is a good example. There are three versions of this curve in this report, Figures 3.2-1, 4.1-2 and 4.1-12. Comments on their applicability and modification for field usage are found in Paragraph 4.1.1.5. The tests that have defined the various DMF's differ significantly in approach and methods. They may use different detection targets (periodic, nonperiodic) for models, different threshold criteria (50 percent, 90 percent probability) and different measures of information content (S/N ratio, contrast). Work is continuing to further refine the DMF, but in the interim period existing data must be used. Results using one DMF can be checked for reasonableness by comparing the results against those from use of another DMF.

The required modulation, m_e, as a function of spatial frequency is taken from the appropriate threshold modulation curves adjusted for field conditions. (See Paragraph 4.1.1.5).

In addition to meeting the DMF requirement, the displayed image must exhibit sufficient signal to noise ratio to be detectable. This requirement will be examined subsequently. For the first analysis, it will be assumed that a high signal to noise ratio is available. This condition will be obtained with most TV systems operating outdoors in the daytime, and with some low light level TV or FLIR sensors operating in a low gain mode.

The next step is to establish a value for m_R, the apparent modulation contrast of the target. Usually, the inherent contrast of the target is known or assumed. Inherent contrast is the contrast that the target appears to have when viewed up close while apparent contrast is the contrast that the target appears to have when viewed at a range, r. Apparent contrast, C_R, is related to inherent contrast, C_o, by the atmospheric contrast transmittance factor, (C_R/C_o). Contrast transmittance is a function of the specific atmospheric conditions and the background against which the target is viewed. If inherent contrast and atmospheric conditions are known, the apparent contrast at the desired viewing range can be computed, using the techniques of (Paragraph 4.3.3.4).

Apparent contrast is related to modulation of the optical image by the following equations, derivable from those of Paragraph 4.3.3.2,

$$m_R = \frac{C_R}{2 + C_R} \qquad C_R > 0$$

$$m_R = \frac{-C_R}{2 + C_R} \qquad C_R < 0 \qquad (4.7\text{-}12)$$

At this point, two of the factors of (Equation 4.7-11), m_R and m_e are known, and it remains to calculate the system square wave response. The sine wave response (MTF) of a system of cascaded components is given by the product of the sine wave responses (MTF's) of each of the components (again assuming a linear system.) For a typical LLLTV system,

$$\tilde{r}_{sys} = \tilde{r}_{MOT}\,\tilde{r}_{OBJ}\,\tilde{r}_{INT}\,\tilde{r}_{CAM}\,\tilde{r}_{EL}\,\tilde{r}_{DIS} \qquad (4.7\text{-}13)$$

where each sine wave response factor is taken at a specific spatial frequency, ψ,

$\tilde{r}_{sys}$ is the system since wave response or modulation transfer factor at the spatial frequency of interest,

$\tilde{r}_{MOT}$ is the sine wave response due to image motion,

$\tilde{r}_{OBJ}$ is the sine wave response of the objective optics,

$\tilde{r}_{INT}$ is the sine wave response of the image intensifier,

$\tilde{r}_{CAM}$ is the sine wave response of the camera tube,

$\tilde{r}_{EL}$ is the sine wave response of the video electronics,

$\tilde{r}_{DIS}$ is the sine wave response of the display.

By taking products at several spatial frequencies, the system sine wave response function or modulation transfer function can be calculated as indicated in Figure 4.7-1. The system square wave response is given by

$$\overset{\sqcap}{r}(n) = \frac{4}{n}\left[\tilde{r}(n) - \frac{\tilde{r}\,(3n)}{3} + \frac{\tilde{r}\,(5n)}{5}\;.\;.\;.\right] \tag{4.7-14}$$

If we are concerned with resolution greater than 1/3 the maximum system resolution, the higher harmonic terms are negligible, and

$$\overset{\sqcap}{r}(n) \approx \frac{4}{n}\,\tilde{r}\,(n) \tag{4.7-15}$$

This is most usually the case, and in this event it is convenient to rewrite (Equation 4.7-13) as

$$\overset{\sqcap}{r}_{sys} \approx \tilde{r}_{MOT}\,\tilde{r}_{OBJ}\,\tilde{r}_{INT}\,\overset{\sqcap}{r}_{CAM}\,\tilde{r}_{EL}\,\tilde{r}_{DIS} \tag{4.7-16}$$

where

$\overset{\sqcap}{r}_{CAM}$ is camera tube square wave response.

The above form is convenient because camera tube data are commonly given as square wave response, whereas sine wave response data are available for the other components.

By carrying out the calculation of (Equation 4.7-16) at the spatial frequency of interest, as determined by (Equation 4.7-9) or (Equation 4.7-10), the suitability of the system in reproducing the desired frequency with the required contrast can be assessed.

The sine wave response function of each component is usually expressed in units which make sense to the manufacturer of that component, hence we have line pairs/mr, TV lines/frame, relative spatial frequency, etc. The following equations relate the various spatial frequencies, for a given optical system. Let:

ψ be angular spatial frequency, line pairs/mr,

ν be spatial frequency, line pairs/mm,

N_{TV} be TV resolution, TV lines/frame height or commonly abbreviated TVL/frame or even TVL,

f be focal length of objective optic, mm,

D be diameter of objective optic, mm,

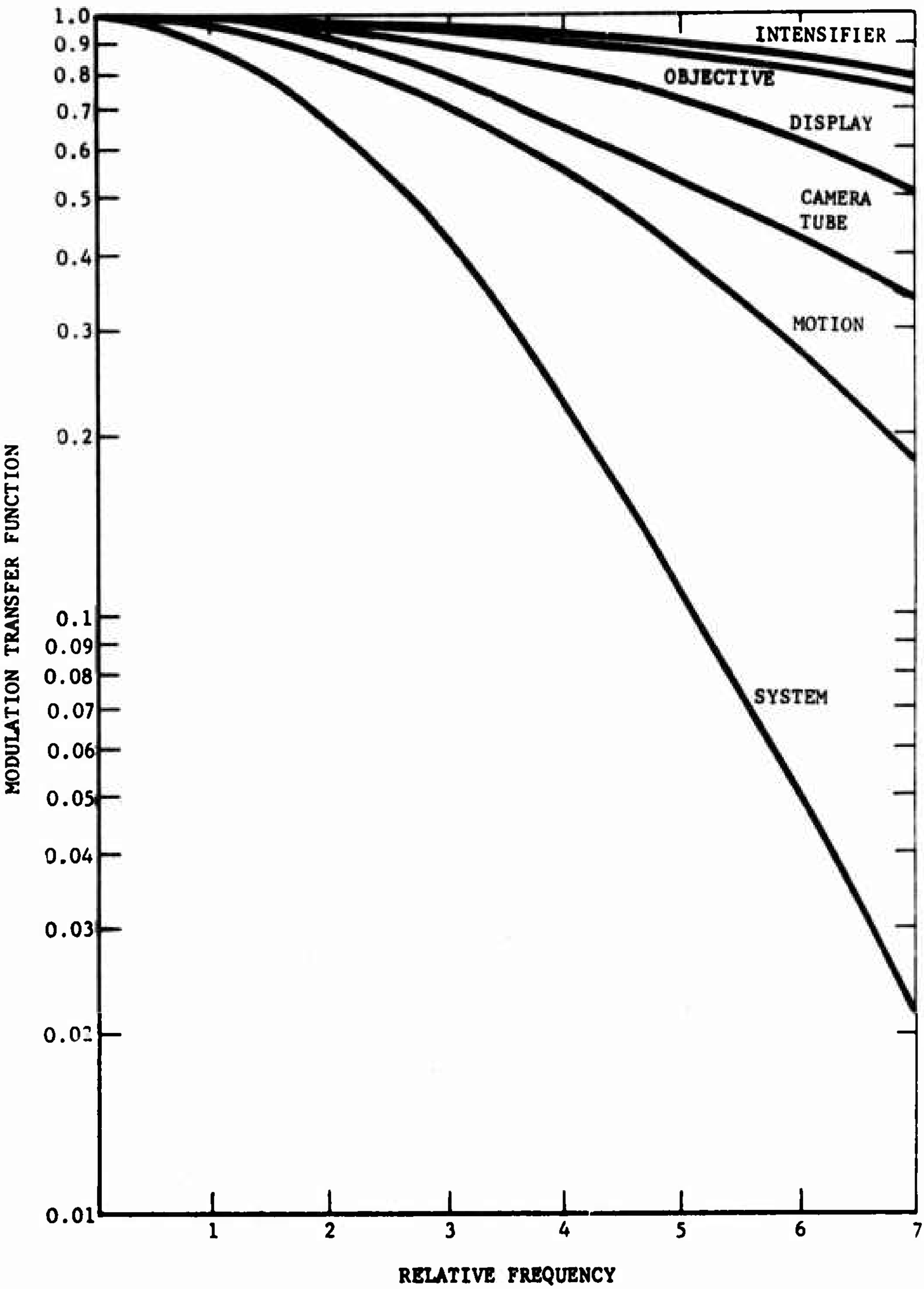


FIGURE 4.7-1. MTF OF A SYSTEM OF CASCADED COMPONENTS

F be focal ratio, f/D,

d be sensor image plane height, mm,

w be image size of a resolved line pair, mm,

λ be radiation wavelength, μm,

q be sensor vertical field of view, mr,

ψ_o be the diffraction limited cutoff angular spatial frequency, line pairs/mr,

ν_o be the diffraction limited cutoff spatial frequency, line pairs/mm.

The relationships in Table 4.7-2 are exact or approximately true for fields of view (total) less than about 30 degrees. (See Section 3.3 for discussion of spatial frequency).

TABLE 4.7-2. VIEWING SYSTEM PARAMETER RELATIONSHIPS

$\nu = \frac{10^3 \psi}{f} = \frac{q\psi}{d}$	line pairs/mm	(4.7-17)
$\nu_o = \frac{10^3}{F\lambda}$	line pairs/mm	(4.7-18)
$\psi_o = \frac{D}{\lambda}$	line pairs/mr	(4.7-19)
$\frac{\psi}{\psi_o} = \frac{\nu}{\nu_o} = 10^{-3}\,\nu F \lambda = \frac{\lambda \psi}{D}$		(4.7-20)
$N_{TV} = 2\,\nu d = 2\,q\,\psi$	TV lines/frame	(4.7-21)
$q = \frac{10^3\,d}{f}$	milliradians	(4.7-22)
$w = \frac{f}{10^3\,\psi}$	millimeters	(4.7-23)

4.7.2.4 TV System Sensitivity

In this paragraph, the relationship between scene radiance, target contrast, and TV system performance is examined. The photons which arrive at the sensor photosurface are converted to an electrical signal. The magnitude of this signal is proportional to the number of photons which are collected and to the responsivity and gain characteristics of the sensor. The signal must compete with the noises which are present in the imaging system, or ultimately inherent in the signal itself. The following paragraphs quantitatively evaluate TV system sensitivity.

The objective optic forms an image at the photosensitive surface of the EO sensor. The on-axis value of the optical image irradiance was given in Section 4.4.2,

$$E_P = \frac{\pi L_s \tau_o}{4F^2} \tag{4.7-24}$$

where

E_P is image irradiance or illumination, W cm^{-2} or lm cm^{-2},

L_s is scene radiance or luminance, W cm^{-2} sr^{-1} or cd cm^{-2},

τ_o is optical passband transmittance of the optics,

F is objective focal ratio or f/number

For a Lambertian reflecting scene of reflectance ρ_s, the image irradiance due to an externally illuminated scene is

$$E_P = \frac{E_s \rho_s \tau_o}{4F^2} \tag{4.7-25}$$

where

E_s is scene irradiance or illumination, W cm^{-2} or lm cm^{-2},

Typical values of scene illumination (visual spectrum) are given in Paragraph 4.3.1.

Using

$$F = f/D \tag{4.7-26}$$

Equation (4.7-25) can be rewritten as

$$E_P = \frac{E_s \rho_s D^2 \tau_o}{4f^2} \qquad (4.7\text{-}27)$$

The photosurface illuminance can be calculated for the available scene illuminance and aperture diameter. Should the calculated value of E_P be equal to or greater than that required to produce full rated sensor output, adequate signal to noise ratio will be present to achieve the full system resolution. Manufacturer's data sheets include curves of signal current output versus light level, as well as recommended values of operating signal current. For example, a typical vidicon camera tube delivers 150 to 200 nanoamperes of signal current for a photosurface illumination of 1 footcandle (Figure 4.5-4). At this value of signal current the full resolution and gray scale capability of the tube will be realized.

If there is insufficient photosurface illumination, a more sensitive camera tube should be chosen (Paragraph 4.5.3). A typical SEC vidicon produces 200 nanoamperes of signal current at a photosurface illumination of 10^{-2} footcandle, while a typical Silicon EBIC tube produces 200 nanoamperes at approximately 10^{-4} footcandle. For more sensitivity, an image intensifier can be coupled to the camera tube.

When the available illumination, including intensification, is insufficient to produce full signal current from the most sensitive camera tube which is practical, the noise limited resolution of the sensor must be calculated, as outlined in Paragraph 4.7.2.5.

4.7.2.5 Viewing System Performance at Low Signal Levels

Soule (34) says that a video signal to noise ratio of 25 is necessary for acceptable images, and a signal to noise ratio of 200 is required before noise becomes unnoticeable. Below a signal-to-noise ratio of 25 the television display will always appear noisy. From this it is expected that television images formed at low light levels will be noisy in appearance, because the video signal-to-noise ratio will be low. It is found that images can be detected with video signal to noise ratios less than unity. (1)

Under conditions of low S/N ratio, it is the S/N ratio that determines observer resolution performance. (See Paragraph 4.1.2.4). In discussing the observer interface with the system display, the appropriate parameter to describe the perceived S/N ratio is the display signal to noise ratio, SNR_D, and not the video signal to noise ratio, SNR_V. The quantity SNR_D accounts for the ability of the observer to integrate the displayed image information over space and time (Paragraph 4.1.2.4). (With respect to Paragraph 4.1.2.4, SNR_D here refers to the area model $SNR_{D/A}$.) Quantitative considerations of SNR_D follow later in this subsection.

The demand modulation function (DMF) was used as a criterion of observer threshold in the calculations of Paragraph 4.7.2.3. In the discussion to follow, SNR_D is used in place of DMF. Rosell maintains (41) that SNR_D is more fundamental than contrast as a measure of observer performance. He states that low-contrast and high-contrast images are equally detectable if their SNR_D values are equal. Although no one has demonstrated it, it is possible that the DMF is only a special case of the more general SNR_D requirement.

Rosell, (41), (61), and (99), has demonstrated for simple rectangular targets that the threshold value of SNR_D, which is designated SNR_{D-T}, is reasonably invariant for a wide variety of target aspect ratios. From his experiments he established SNR_{D-T} equal to 2.8 for 50 percent probability of detection. This was shown in Figure 4.1-22.of this resport. From that figure, it is seen that SNR_D equal to 5.3 gives nearly 100 percent probability of detection.

Rosell then extended the analyses and experiments to the detection of bar patterns. Like Schade (117), he calculates the SNR_D in a single bar of the bar pattern, and assumes that if this single bar is detected with nearly 100 percent probability, the pattern of bars is detectable. Using an SNR_D equal to 5.3, Rosell has found reasonable agreement between measurement and theory. Rosell (41) has found that the SNR_D required to detect the bar pattern may be a slowly varying function of bar length-to-width ratio. For longer length-to-width ratios, a slightly higher SNR_D is required. This refinement will be neglected in the exposition that follows.

Just as laboratory measured values of contrast threshold must be adjusted upwards to account for actual conditions in the field, (Paragraph 4.1.1.5) it is also likely that correction factors may have to be applied to SNR_D threshold. There does not appear to be any definitive work on the subject at this time. Thus in the analyses that follow, it should be assumed that the observer is vigilant, knows what target he is looking for, and knows approximately when and where it will appear. (76).

4.7.2.5.1 Noise Limited Resolution

Noise limited resolution theories have followed the developments of Schade (117), who demonstrated for the first time that MTF and noise in EO systems could be evaluated on a unified basis and measured with practical instrumentation, yielding objective data on the performance of practical system elements and complete systems. The unified treatment of MTF and noise begins by establishing a signal to noise ratio, per unit area, at the input to the system. At the system input, the only source of noise is the photoelectron shot noise inherent in the signal. In the various stages of the sensor system, the signal to noise ratio is degraded by two mechanisms. The first is the addition of noise at the various

stages (e.g., dark current noise, scanning beam shot noise, preamplifier noise, etc.). The second signal to noise ratio degradation results from the spreading of small images as they are convolved with the spread functions of the individual system components. This spreading results in a loss of peak signal.

The signal to noise ratio which is effective to the viewer of the display is greater than that measured in the video amplifier, for two reasons. The observer is able to integrate over large areas to make a judgement on whether a target image is present. He is also capable of integrating the information from several successive frames in making his judgement. (See Paragraph 4.1.2).

Rosell has carried the concept the furthest, and has presented a number of useful equations (41), (61), Chapter 14 of (99), and Chapter 22 of (100). One of the most basic equations is

$$SNR_D = \left(a\ t_e\ \Delta f/A\right)^{1/2}\ SNR_V \qquad (4.7\text{-}28)$$

where

SNR_D is the signal to noise ratio apparent to the observer viewing the display,

a is the area of the target image to be detected,

t_e is the integration time of the eye,

Δf is the video bandwidth,

A is the effective photosurface area,

SNR_V is the signal to noise ratio measured in the video amplifier, for a target image large with respect to the point spread function of the sensor.

The above equation is a quantitative statement of the notions presented in previous paragraphs, including Paragraph 4.7.2.5. As a target image occupies a larger fraction of the display area, it becomes more detectable. Also, the eye integration time, in effect, sets a noise bandwidth much less than the video bandwidth of the system.

When bar patterns (see Figure 3.3-3) are to be detected and resolution is expressed in TV lines (Equation 4.7-28) becomes

$$SNR_D = \left(t_e\ \Delta f/b\right)^{1/2}\ \frac{\ell^{1/2}}{N_{TV}}\ SNR_V, \qquad (4.7\text{-}29)$$

where

b is picture aspect ratio, frame width to frame height,

ℓ is bar length to width ratio.

N_{TV} is bar pattern frequency, TV lines/frame height.

(Note the image size and resolution requirements of Paragraphs 4.7.2.1 and 4.7.2.2 still apply and the required SNR_D value is based upon the displayed image requirements.) Calculations of the video signal-to-noise ratio, SNR_V, can become somewhat complicated, depending upon the sensor complexity and the number of significant noise sources. For a sensor in which the only significant source of noise is the photoelectron shot noise inherent in the signal, and which has unity MTF out to the spatial frequency of interest,

$$SNR_v = \frac{\text{peak signal}}{\text{rms shot noise}} = \frac{i_{max} - i_{min}}{\sqrt{2e\left(\frac{i_{max} + i_{min}}{2}\right)\Delta f}} \qquad (4.7\text{-}30)$$

where

i_{max} is the scene highlight signal current at the photosurface, amps

i_{min} is the scene lowlight signal current at the photosurface, amps

e is the electronic charge, 1.6×10^{-19} amp seconds,

Δf is the video bandwidth, Hz.

For a TV system, where signal is integrated for a frame, the value of signal current is

$$i = R\,A\,E \text{ amps} \qquad (4.7\text{-}31)$$

where

R is sensor responsivity, amps/watt,

A is sensor active area, cm^2,

E is image irradiance, watt cm^{-2}.

If the sensor were a FLIR or other nonintegrating type, the sensor active area, A, would be replaced by the individual detector active area, a_D. But since the TV camera integrates or accumulates the input signal, the charge on each elemental area, a_D, is proportional to the frame time. The increase in signal-to-noise ratio for an integrating sensor over a nonintegrating sensor is proportional to A/a_D or the ratio of the frame time to the dwell time.

The value of E_{min} and E_{max} are found from Equation (4.7-25), when laboratory measurements are made. When viewing through an atmosphere, the effect of atmospheric transmittance must be considered. This leads to a rephrasing of Equation (4.7-30) in terms of television contrast, which is per Equation (4.3-10),

$$C = \frac{i_{max} - i_{min}}{i_{max}} \qquad (4.7\text{-}32)$$

and

$$SNR_V = \frac{C\ i_{max}}{\left[(2-C)\ e\ i_{max}\ \Delta f\right]^{1/2}} \qquad (4.7\text{-}33)$$

Now the value apparent target contrast (see Paragraph 4.3.2) can be used.

The next step is to consider the effect of MTF upon the display signal-to-noise ratio. It has been common practice to simply multiply (Equation 4.7-29) by the sine wave response factor at that spatial frequency

$$SNR_D = \left[t_e\ \Delta f/b\right]^{1/2} \frac{\ell^{1/2}\ \tilde{r}}{N_{TV}}\ SNR_V \qquad (4.7\text{-}34)$$

where $\tilde{r}$ is the MTF at the specific value of N_{TV}. This is justified on the basis that the MTF acts to reduce peak signal and thus the signal-to-noise-ratio decreases in direct proportion. Rosell reasons that both the signal and the mean square noise are decreased equally in the target image area, and therefore the SNR_D equation should be multiplied by the square root of the MTF.

$$SNR_D = \left[t_e\ \Delta f/b\right]^{1/2} \frac{(\ell\tilde{r})^{1/2}}{N_{TV}}\ SNR_V \qquad (4.7\text{-}35)$$

The reader is referred to one of the more recent Rosell papers, (41), (61), or (113) for an exposition of this line of reasoning. These papers also justify the use of the sine wave response factor, $\tilde{r}$, when viewing bar targets.

Rosell has conducted experiments which show that a value of SNR_D equal to 5.3 is required for a high probability (>95 percent) of detection of a single bar of a bar pattern. A value of t_e = 0.2 second is assumed. Using these values and solving Equation (4.7-35) for N_{TV}, Rosell has calculated the noise-limited resolution of an intensified silicon EBIR (EBS) camera. The MTF of this camera is shown in Figure 4.7-2, and the calculated resolution in Figure 4.7-3. Rosell states that computed values compare to the measured values to within the experimental errors. The intensified silicon EBIR camera approaches photoelectron shot noise limited performance very closely. In other types of camera tubes, additional sources of noise become important, and a more complicated expression for SNR_V is required. These are developed in Chapter 14 of (99) and Chapter 22 of (100). They will not be considered here, as they are outside the scope of this treatment.

Equations such as 4.7-35 and curves such as shown in Figure 4.7-3 have no built-in limitation. They allow for the viewing of ever-noisier imagery as the resolution requirement is relaxed. In actual fact, however, imagery at very low signal-to-noise ratios is not useful in field applications. A resolution pattern may be visible through the "snow" on the display, but real targets will be difficult to distinguish. A comparison between bandwidth-limited resolution and noise-limited resolution was made in Figures 3.3-11 and 3.3-12. Generally, TV system resolution which is noise-limited to 200 or 250 TV lines per frame height represents a lower useful limit.

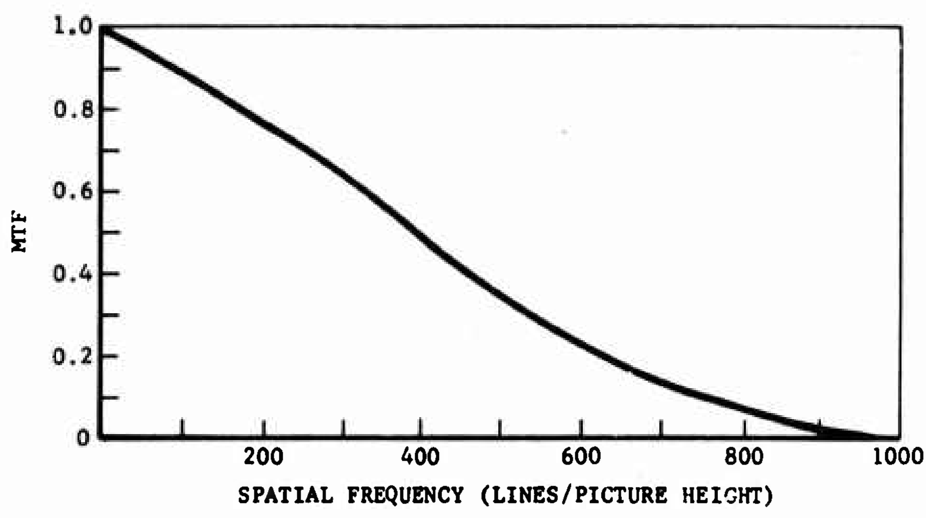


FIGURE 4.7-2. MTF, TYPICAL 40MM I-EBS CAMERA (61)

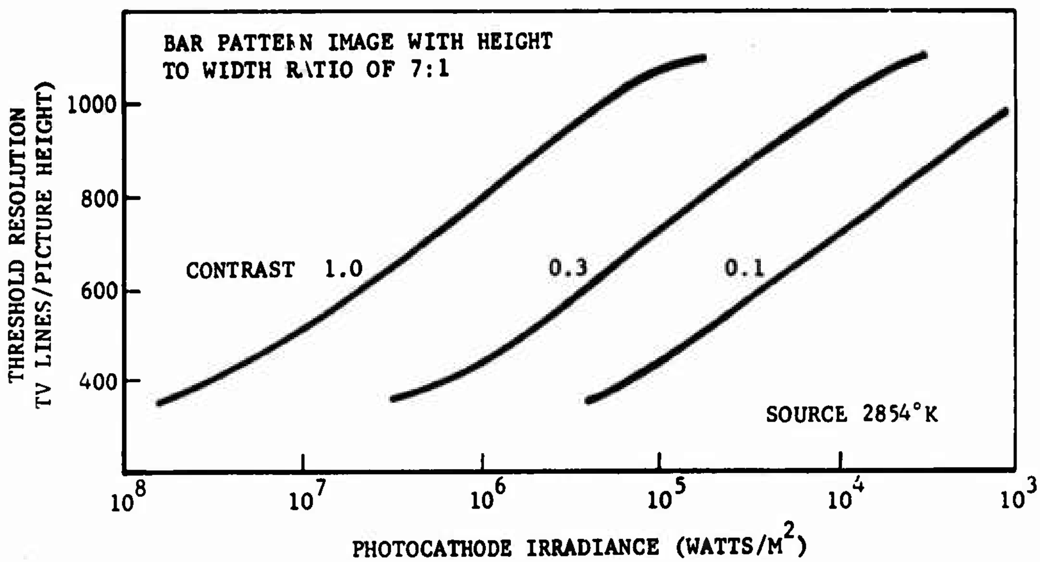


FIGURE 4.7-3. THRESHOLD RESOLUTION VERSUS PHOTOCATHODE IRRADIANCE FOR 40MM I-EBS CAMERA (61)

4.7.2.6 Direct View Imaging System Resolution

The function of the direct view image intensifier system is to increase the brightness of an image of a low light level scene. The viewer then is able to take advantage of his keener resolving power at the higher light level. (See Figure 4.1-3.) Sufficient brightness gain (Paragraph 4.5.2) should be provided in the system so that the viewer is using his photopic vision (Paragraph 4.1.1.1). The function of an image converter system is to present a visual image of a nonvisual target. Again, the image brightness should be sufficient to provide photopic viewing.

For all practical purposes, the signal-to-noise ratio in a direct view imaging system is determined solely by the photoelectron shot noise inherent in the signal. (For devices with high leakage current, the shot noise due to dark current may have to be considered at low signal levels.) This means that the analysis of the preceding subsection is also applicable to direct view imaging systems. The essential difference is that there is no

video amplifier in which to measure the signal. Substituting Equations (4.7-33) and (4.7-31) into (4.7-28), results in the following expression for the display signal-to-noise ratio perceived by the observer

$$SNR_D = \left[a\ t_e\right]^{1/2} \frac{C}{(2-C)^{1/2}} \left[\frac{R\ E_{max}}{e}\right]^{1/2} \qquad (4.7\text{-}36)$$

When a bar target is viewed and the MTF of the imaging system taken into account,

$$SNR_D = \left[\frac{\ell\ t_e}{4}\right]^{1/2} \frac{\left[\tilde{r}\ (\nu)\right]^{1/2}}{10\ \nu} \frac{C}{(2-C)^{1/2}} \left[\frac{R\ E_{max}}{e}\right]^{1/2} \qquad (4.7\text{-}37)$$

where

- ℓ is the bar length to width ratio
- t_e is the eye integration time, seconds
- ν is the spatial frequency of the bar target (at the photosurface), line pairs/mm ($10\,\nu$ is line pairs/cm, for dimensional correctness)
- $\tilde{r}(\nu)$ is the MTF of the imaging system at the spatial frequency ν
- C is apparent contrast, defined by Equations 4.3-22 and 4.3-10
- R is the responsivity of the first photosurface, amps/watt
- E_{max} is the highlight irradiance on the first photosurface, watts/cm^2
- e is electronic charge, 1.6×10^{-19} amp seconds

Using a value of 5.3 for the threshold value of SNR_D for a single bar, t_e equal to 0.2 second, a length to width ratio of 5 to 1 as in the Air Force Bar Chart (Figure 3.3-3), and solving Equation (4.7-37) for noise limited resolution,

$$\nu_{threshold} = 2.35 \times 10^7 \left[\tilde{r}(\nu)\right]^{1/2} \frac{C}{\sqrt{2-C}} \sqrt{R\ E_{max}} \qquad (4.7\text{-}38)$$

where

$\nu_{threshold}$ is noise limited resolution, line pairs/mm

R is first photosurface responsivity, amps/watt

E_{max} is highlight photosurface irradiance, watts/cm^2

Note also that luminous quantities may be used in the last factor in Equation (4.7-38), so that

$$R\, E_{max} = S\, E_{v_{max}} \tag{4.7-39}$$

where

S is luminous sensitivity, amps/lumen, as defined by Equation (4.5-5)

$E_{v_{max}}$ is highlight illumination, lumens/cm^2

Curves of noise limited resolution as a function of photosurface irradiance are very similar to those of Figure 4.7-3, presented in the previous subsection.

4.7.2.7 FLIR System Sensitivity

Although the terminology and symbology are different, the same techniques and line of reasoning are used in low light level TV, direct view imaging, and FLIR system performance calculations. The common measure for FLIR system performance is minimum resolvable temperature difference (MRT), which was introduced in Paragraph 4.5.4.3. The MRT is at present the demand modulation function for an observer using a FLIR set. Calculations of MRT implicitly assume that the spectral emissivities of target and background are equal, constant, and unity. Although it is possible to calculate a signal-to-noise ratio due to emissivity differences, this is not commonly done.

Rosell (41), (61), (113) has derived an MRT equation starting from the same basis which led to the TV and image intensifier performance equations. When viewing a 7:1 length to width bar target (see Paragraph 4.5.4.3) and using Rosell's value of 5.3 for threshold signal-to-noise ratio, his equation becomes

$$MRT = (b\, n_d)^{1/2} \frac{\psi}{\left[\tilde{r}\,(\psi)\right]^{1/2}} \; \frac{18 \times 10^3\, k\, f}{D^2\, \tau_o\, \eta_s^{1/2}\, D^*\,(\Omega)\, \frac{\partial L}{\partial T}} \tag{4.7-40}$$

where

b is image aspect ratio, width to height

n_d is number of detectors in the FLIR array

ψ is bar target spatial frequency, line pairs/milliradian

$\tilde{r}(\psi)$ is the sine wave response factor of the FLIR set at ψ

k is the interlace ratio

f is the focal length of the FLIR objective, cm

D is objective diameter, cm

τ_o is optical transmittance

η_s is scanning efficiency, or ratio of time spent actively scanning to total frame time

$D^*(\Omega)$ is the specific detectivity of the FLIR detector, cm $(Hz)^{1/2}$ w^{-1} sr^{-1}

$\frac{\partial L}{\partial T}$ is the change in radiance for a small temperature change, w cm^{-2} sr^{-1} K^{-1} (see Paragraph 4.3.2.3)

The factor $D^*(\Omega)$ is the commonly accepted measure of the sensitivity of an infrared detector (83), (84), (86).

It is a measure, which for most IR detectors, is independent of area and electrical bandwidth. The greater the value of D^*, the more nearly perfect the detector. The dependence upon solid angle, $D^*(\Omega)$, infers that sensitivity is a function of the solid angle through which the detector receives radiation. This is true of most detectors working in the 8 to 14μm window, where cold shielding to reduce background radiation is necessary to achieve optimum performance from a detector. In this case, cooled baffles are provided to prevent radiant flux from reaching the detector, except that which arrives from the objective lens.

Sendall and LLoyd (112) give another equation for MRT, based upon more traditional measurement methods.

MRT = (NETD) x (signal rolloff) x (noise rolloff) x (spatial integration) x (temporal integration) x (threshold SNR)

$$MRT = NETD \times \frac{1}{\sqcap_r} \times \rho_n^{1/2} \times \frac{\psi_t}{\psi_r} \sqrt{\frac{\theta_n}{\theta_d}} \times \frac{1}{\sqrt{t_e \dot{F}}} \times 2.7 \qquad (4.7\text{-}41)$$

where

NETD is noise equivalent temperature difference, °C

$\sqcap_r$ is FLIR sensor square wave response at the bar target spatial frequency, ψ_t

ψ_t is the bar target spatial frequency, line pairs/milliradian

ψ_r is a reference spatial frequency, line pairs/milliradian

$$\psi_r = \frac{1}{2\,\theta_d}$$

θ_d is detector angular subtense (instantaneous field of view) in the direction of scan, milliradians

θ_n is detector angular subtense normal to the direction of scan, milliradians

t_e is the eye integration time (0.2 second)

$\dot{F}$ is frame rate, frames/second

ρ_n is a noise rolloff factor

$$\rho_n = \frac{\int_0^{\infty} \tilde{r}_e^2\, \tilde{r}_d^2 \left[\dfrac{\sin \dfrac{\pi \psi}{2 \psi_r}}{\dfrac{\pi \psi}{2 \psi_r}}\right]^2 d\psi}{\psi_t} \qquad (4.7\text{-}42)$$

$\tilde{r}_e$ is sine wave response of the sensor electronics

$\tilde{r}_D$ is the sine wave response of the display

The concept of NETD, noise equivalent temperature difference, was introduced in Paragraph 4.5.4.3 as the traditional measure of system sensitivity. It is the value of large target temperature difference which produces a peak signal to RMS noise ratio equal to unity. It is properly used as a design verification equation, rather than a performance prediction equation. One relationship for NETD is (112).

$$\mathrm{NETD} = \frac{(P\,q\,\dot{F})^{1/2}}{\theta_d\,\theta_n}\;\frac{\sqrt{2}}{D\,\eta_d^{1/2}\,\tau_o\,\tau_a\,\eta_c\,(\eta_q\,\eta_s)^{1/2}\,\frac{\partial M}{\partial T}\,D^{**}} \qquad (4.7\text{-}43)$$

where

p is total field of view in the direction of scan, milliradians

q is total field of view in the direction normal to scan, milliradians

η_c is the cold shield efficiency (60)

η_q is the quantum efficiency of the detector (60)

τ_a is atmospheric transmittance (unity for laboratory measurements)

D^{**} is the specific detectivity of the detector when viewing a 300K background, without benefit of cold shield, cm $(\mathrm{Hz})^{1/2}$ w^{-1} sr^{-1}

$\frac{\partial M}{\partial T}$ is the change in radiant emittance for a small temperature change, w cm^{-2} K^{-1} and the other symbols are defined following Equations (4.7-40) and 4.7-41)

At the present time, MRT is the accepted measure of system performance. Substituting Equations (4.7-43) into (4.7-41),

$$\mathrm{MRT} = \left[\frac{p\,q}{\eta_d\,\theta_d\,\theta_n}\right]^{1/2}\;\frac{\psi_t\,\rho_n^{1/2}}{\tilde{r}}\;\frac{17\times 10^3}{D\,\tau_o\,\tau_a\,\eta_c\,(\eta_s\,\eta_q)^{1/2}\,D^{**}\,\frac{\partial M}{\partial T}} \qquad (4.7\text{-}44)$$

Equation (4.7-44) is in a form which is useful for assessing FLIR system parameter value tradeoffs. The first factor in the equation is a measure of the fraction of the total field of view which is covered by active detectors. The greater this fraction, the more sensitive the FLIR set. Sensitivity is also proportional to aperture diameter, as is expected for a system limited by background noise (signal proportional to D^2, noise to D). The MRT is independent of frame rate. This assumes that the eye integration time effectively sets the system bandwidth, and that the frame rate is sufficiently high to avoid flicker.

It is important to note that the values of $D^*(\Omega)$ and D^{**} used in the preceding equations are for 300K background (assuming a terrestial target). Manufacturers' data sheets commonly give D^*, $D^*(\Omega)$, and D^{**} values for 500K objects. Clearly, these data are not directly applicable to viewing terrestial backgrounds at a temperature near 300K. Appendix II of Kruse, et al., (126) gives an approximate method of converting D^* (500K) to D^* (other temperatures). For more precise analyses, it is noted that the quantities τ_o, τ_a, η_q, D^{**}, and $\partial M/\partial T$ are spectrally dependent. Therefore, the product of these quantities should be replaced by what has been called a Radiation Function,

$$\int_0^\infty \tau_{o_\lambda} \tau_{a_\lambda} \eta_{q_\lambda}^{1/2} \, D^{**}_\lambda \frac{\partial M}{\partial T} \, d\lambda$$

The spectral plot of D^{**} is given on manufacturers' data sheets. The spectral values of $\partial M/\partial T$ can be found from radiation tables, such as Pivovonsky and Nagel (89).

It is desirable to compare Rosell's Equation (4.7-4), to Sendall and Lloyd's Equation (4.7-44), since both purport to describe the same performance parameter. The first difference is that Rosell's value of signal-to-noise ratio was chosen to give nearly 100 percent probability of detection, whereas Sendall and Lloyd's value was chosen for 50 percent probability. Therefore, the constant in Equation (4.7-44) should be multiplied by a factor of approximately 1.9 to put the two formulations on the same basis. Next, as was mentioned in Paragraph 4.7.2.4, Rosell has chosen to use $(\tilde{r})^{1/2}$ in place of $\tilde{r}$. Further, Sendall and Lloyd have noted that ρ_n, the noise rolloff factor, is a refinement which can be ignored, especially in a first analysis (112). Rosell has not explicitly considered ρ_n in his analysis, but rather has used $(\tilde{r})^{1/2}$ instead of $\tilde{r}$ to account for signal-to-noise ratio rolloff. This is not precisely the same concept as $\rho_n^{1/2}$, but the fit to experimental data is probably equally good.

Note also that $\partial L/\partial T$, the change in radiance with temperature, appears in one equation, while $\partial M/\partial T$, the change in radiant emittance, appears in the other. The two are related by $M = \pi L$, for a Lambertian (ideally diffuse) radiator.

To complete the comparison, it is necessary to employ the following relationships. The D*(Ω) and D** of a detector are related by (112), (60).

$$D^*(\Omega) = D^{**}\,\eta_q^{1/2}\,\eta_c\,2F \qquad (4.7\text{-}45)$$

Also, it is apparent that the interlaced array of detectors just fills the field of view in the direction normal to scan, so that

$$n_d\,\theta_n\,k = q \qquad (4.7\text{-}46)$$

When these substitutions are made, the fact that Rosell assumed $\theta_n = \theta_d$ taken into account, and the difference between $(\Upsilon)^{1/2}$ and $\rho_n^{1/2}$ taken as compensating factors, the two Equations (4.7-40) and (4.7-43) agree, except that the constant factor in Equation (4.7-40) is greater by approximately $\sqrt{2}$. This makes Equation (4.7-40) more conservative by that amount.

FLIR sets are quite useful in detecting "hot spots" at relatively long ranges. These hot spots may be due to operating engines or other thermal sources much hotter than their surroundings. In this case, the hot spot can be detected even though the target is not resolved. To analyze performance against this sort of target, it is more appropriate to convolve the point spread function of the FLIR set with the target image, and then calculate signal-to-noise ratio, starting from a basic equation such as Equation (4.7-28).

4.7.3 SIGNAL PROCESSING

4.7.3.1 Bandwidth Requirements

If a television system views a vertically oriented sine wave test pattern whose spatial frequency is N_H TV lines/frame height, the electrical frequency generated by scanning is equal to

$$f_H = \frac{n_f\,N_H\,b}{2\,t_f\,\eta_H}\ \mathrm{Hz} \qquad (4.7\text{-}47)$$

where

n_f is the number of scan lines per frame time

N_H is the test pattern spatial frequency, TV lines per frame height

b is the frame aspect ratio, horizontal to vertical

t_f is the frame time in seconds

η_H is horizontal scanning efficiency. (Scanning efficiency is the ratio of the active scan time to the active scan time plus retrace time of the scanning beam.)

For the standard 525 line system, using 1/30 second frame time, a horizontal scanning efficiency of 0.84, and a frame aspect ratio of 4/3,

$$f_H = 1.25 \times 10^4 \; N_H \quad \text{Hz}$$

or

$$N_H = 80 \text{ TV lines/frame height, per MHz.}$$

Thus to achieve a horizontal resolution of 1000 TV lines per frame height, a bandwidth of at least 12.5 MHz is required. In addition to this, the system MTF must be greater than the DMF (see Paragraph 4.7.2.3). The nomenclature which expresses horizontal resolution per frame height is sometimes confusing. To be clear, horizontal resolution refers to resolution measured in a horizontal direction on the display, so that the raster lines cut across the bar pattern, which is oriented vertically on the display. The use of frame height as the space dimension is perhaps convenient, but to the unitiated, confusing. In visualizing horizontal resolution, one should mentally step back from the display to eliminate the raster lines from consideration. The number of scan lines per frame, e.g., 525, should not be confused with resolution.

The vertical resolution of a TV system is determined not by bandwidth, but by the finite number of samples in the vertical dimension, due to the raster. Vertical resolution is always less than the value of n_f, the number of scanning lines per frame. Not all of the scanning lines are active in reading signal, as the time allotted for some of them is used in the process of vertical retrace. For the standard 525 line system, about 490 scan lines are active in reading signal. In addition to this, it is obvious that scene details or bar targets are not always apt to line up in perfect register with the scanning raster. Through experience, it has been found that the limiting vertical resolution for a well adjusted TV system is

$$N_H = k_v \, n_r, \text{ TV lines/frame height} \qquad (4.7\text{-}48)$$

where

k_v is a factor less than unity, usually called the "Kell factor,"

n_r is the number of active scanning lines in the raster.

The commonly accepted value of k_v is 0.70. Values of 0.5 to 0.82 were proposed early in the history of television. It is important to realize that k_v equal to 0.7 will not be realized for a poorly interlaced system, i.e., one in which the scan lines are not evenly spaced.

Table 4.7-4 lists some of the properties of the commonly used scanning standards. It is assumed that the frame time is 1/30 second, and that the aspect ratio is 4:3.

TABLE 4.7-4. PROPERTIES OF COMMONLY USED TV SCANNING STANDARDS

Scan Lines/ Frame	Active Scans/ Frame	Vertical Resolution (max) TV Lines/Frame N_V	Horizontal Resolution Factor (TV Lines/MHz)	Bandwidth for $N_H = N_V$ (MHz)
525	490	340	80	4.3
875	809	575	46.6	12.3
945	874	600	42.4	14.1

Video bandwidths required for FLIR sets are substantially less than TV video bandwidths, because of the large number of channels receiving parallel information. This means that IR detectors used in FLIR sets do not have to have megaHertz response rates. However, once the video information is multiplexed for display on a single gun CRT, bandwidth requirements per resolution element are similar to those of a TV system. The following equations give the bandwidth requirement of a FLIR video channel.

It has been common practice in FLIR systems to optimize the bandwidth in each detector/amplifier channel so that the electrical frequency response is flat to

$$\Delta f = \frac{1}{2\,t_d}\ \text{Hz} \tag{4.7-49}$$

where

t_d is the dwell time of a detector element, seconds.

For contiguous scanning of a conventional raster (or interlaced scanning where successive fields are contiguous), this is

$$\Delta f = \frac{p\,q}{2\,n_d\,\theta_d\,\theta_n\,\eta_s\,t_f}\ \text{Hz} \tag{4.7-50}$$

where

p, q	are the field of view in azimuth and elevation, mr,
n_d	is the number of detectors,
θ_d, θ_n	are the instantaneous fields of view in azimuth and elevation, mr.
η_s	is the scanning efficiency, i.e., the fraction of time spent actively scanning,
t_f	is frame time, seconds.

4.7.3.2 Spurious Responses

Two types of spurious, or false, sources of image information can be encountered in EO imaging systems. The first is spurious resolution, and the second is referred to as aliasing.

Spurious resolution arises when the MTF of the viewing system does not monotonically approach zero but rather crosses through zero, goes negative, and perhaps dies out in an oscillatory fashion. Such MTF's arise from sharply defined point spread functions. One example is the sin X/X MTF of a rectangular FLIR detector. Another is the $J_o(X)$ (Bessel function) MTF due to sinusoidal image motion. In these cases, when bar patterns containing frequencies higher than the first zero of the MTF are imaged, the higher frequencies can be resolved, but reversed in tone (phase) just as the MTF curve predicts. Figure 4.7-4 (115) exhibits this phenomenon.

Aliasing arises because of the raster scanning process of TV and FLIR systems. The sampling theorem states that a function whose maximum frequency component is f_m can be fully specified by sampling at equal intervals not exceeding 1/2 f_m. Sampling at wider intervals constitutes undersampling, and in general the original function cannot be recovered. Thus, a sine wave must be sampled at least once each half cycle to be faithfully reproduced. All of this says that there is a limit to the vertical resolution of a TV system because of the raster process, which seems pretty intuitive.

However, the consequences can be more severe. A function which has been undersampled contains contributions from high frequency components in the original function, which now masquerades as low frequency components, which impart false detail to the image. A good homely example is the Moiré pattern which is produced when a half-tone photograph is viewed through a mesh of about the same spacing as the half-tone dots. Figure 4.7-5, which has been taken from Chapter 15 of (99), graphically illustrates how false frequency data is generated by undersampling.

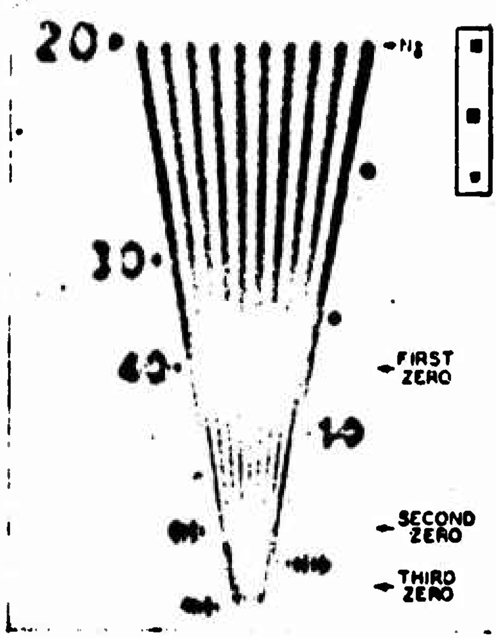


FIGURE 4.7-4. TEST PATTERN IMAGE FORMED BY SQUARE APERTURE (DEFOCUSED LENS) AS SHOWN BY PINHOLE IMAGES (115)

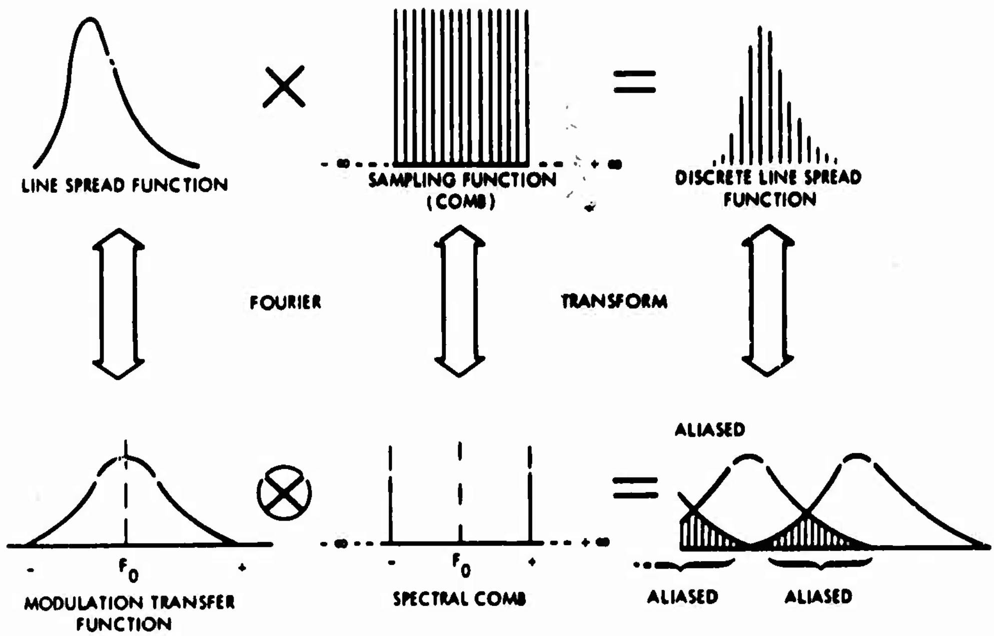


FIGURE 4.7-5. THE SPECTRAL ALIASING OF A SAMPLED LINE SPREAD FUNCTION (40)

Schade, in Appendix B of (7), presents an analysis of raster sampling of a pattern of frequency f_m. He shows that the output function contains not only the original signal frequency f_m, but also beat frequencies, which are the sum and difference of the signal frequency f_m and the raster frequency f_r. It is the difference frequencies which can appear on the display and degrade image quality.

Clearly, it is not possible to eliminate high frequency detail from the scene. Schade concludes that it is necessary to choose n_r, the number of active scanning lines, such that $N_{0.26} \leq n_r \_ N_{0.05}$, where $N_{0.26}$ and $N_{0.05}$ are the frequencies, TV lines/frame height, at which the camera MTF is 26 percent and 5 percent, respectively. A design for best utilization of bandwidth would select $n_r = N_{0.26}$, while maximum resolution would require $n_r = N_{0.05}$.

In addition, flat field viewing is desirable to eliminate the interference due to line structure. The viewer should place his eyes at a distance at least 4 times the display height for a standard 525 line system.

4.7.4 SPECIFICATION PHILOSOPHY

The problem of what and how to specify for procurement of optimized imaging systems has received critical attention since the Department of Defense and the Services determined that their specification practices were not providing systems with the field performance that they desired. As a result, in the interest of defining good specifications and providing standard tests and terminology, a specialty group for imaging systems has been formed by IRIS (Infrared Information Symposium) and publications relating to specification practice has been issued by the Institute for Defense Analyses (IDA). The content of this section is based upon the information contained in Research Paper No. P-467, "Specification for Electronic Image-Forming Devices," and Research Paper No. P-676, "A Guide for the Preparation of Specifications for Real-Time Thermal Imaging Systems," both edited by L. M. Biberman.

The consideration for providing maximum flexibility for tradeoffs to the system designer has already been discussed (Section 2.2) and specification practice should consider this need as practicable. The specification should be concerned with system performance parameters that relate to field success and not parameters that are merely traditional or easy to measure. The number of requirements should be minimized to what is essential for system performance. Requirements in addition to this result in added costs due to unnecessary testing and restrict the number of options open to the system designer in configuring the imaging system. The system performance requirements should be determined from mission requirements considering the viewing requirements of the observer. Testing, including physchometric testing if observer requirements are in doubt, should be sufficiently thorough to establish the relationships between specified system performance parameters and imaging performance in the field.

4.7.4.1 Requirements of Performance Measure

From IDA Report No. P-676 (7) there are four characteristics that an acceptable performance measure should possess:

(1) Predictability from elementary parameters.

(2) Laboratory measurability.

(3) Correlation with field performance.

(4) Comparable accuracy for Items (1), (2) and (3).

It is premature to assume these qualities are mutually and rigorously achievable today, but they remain a valid philosophical guide. Compromises such as laboratory measurable quantities that relate to field performance may adequately define the system performance without an airtight prediction behind it.

For system evaluation the performance quantity should be a measure of the performance of the assembled system. Component or subsystem performance parameters are suitable for component level specifications but are generally not desirable for system measures unless they are rigorously correlative to a system performance measure. In this context when a system laboratory measure is established as effective in defining overall system performance, the terminology, test methods and test procedures should be standardized to facilitate general usage of the measure. Presently, the following performance tests should be considered as requirements for overall system performance:

(1) FLIR sets.

  (a) MRT

  (b) MTF (OTF)

  (c) Signal Transfer Function.

(2) LLLTV Systems (including intensifiers)

  (a) Shades of gray

  (b) MTF (OTF)

  (c) Limiting resolution as a function of light level.

APPENDIX A

PHOTOMETRIC/RADIOMETRIC RELATIONSHIPS

1.0 GENERAL

Radiometry is the science which deals with the concepts and measurements associated with the radiation processes. The special case of radiometry which deals exclusively with visible radiation is called photometry. Photometry as a discipline has a history that stands independent of the development of the science of radiometry and has developed its own unique terminology even though visible radiation obeys the laws of radiometry.

Both photometric and radiometric systems apply to the descriptions of the imaging system. It is appropriate to describe the display/man interface in photometric terms because they very specifically apply to the needs of human vision. It is appropriate to describe the input radiation to the photo sensor in radiometric terms since in general the spectral response of the photo sensor will not match that of the human eye (Section 3.1).

For reasons of economics (less expensive testing facilities) and tradition, photometric terms are often applied to TV and intensifying tubes instead of using the more appropriate radiometric terminology. In order to predict the performance of the sensor it is necessary to convert from photometric to radiometric terms to determine the resultant sensor signal current derived from input radiation. This additional process adds a large amount of confusion to the sensor analysis while at the same time introducing conversion errors which lead to additional uncertainties in predicting sensor performance. The proper description for the sensor is its spectral response curve. The output from the sensor can then be computed from

the interaction of the spectral response $R(\lambda)$ and spectral irradiance (input radiation) $E(\lambda)$ by the integral

$$i = \int_{\lambda_1}^{\lambda_2} R(\lambda)\ E(\lambda)\ d\lambda \quad \text{(See also 4.7.2.)}$$

where λ_1 to λ_2 represents the wavelength region where $R(\lambda)\ E(\lambda)$ is non ro.

Since photometry is concerned with visible radiation, it is necessarily concerned with the psychophysical reaction of the eye in how it perceives the spectrum of visible color. The eye does not perceive all visible colors as equal strengths when the radiant flux for all colors of the spectrum is the same. The normalized eye sensitivity curve for the standard eye is shown in Figure 4.1-1 and forms the basis for defining photometric quantities. This curve is called the luminosity curve (the photopic eye) and it should be noted that as the eye is dark adapted (scotopic eye) the eye response will shift both in spectral distribution and sensitivity and that input radiation flux will be perceived differently by the observer (i.e., the photometric terms no longer properly describe the visual sensations of the observer). There does exist a set of parallel photometric units for the dark adapted or scotopic eye, but as values for natural and artificial illuminance are almost exclusively in photopic terms, the scotopic system will not be treated here. Visible radiation is still measured in terms of the effects it would have on the standard eye.

Sources of different spectral content effect differences in visual perception according to the eye luminosity curve. It is necessary to define a specific spectral content to discuss the sensations the eye perceives. Sources of other spectral content can then be compared to the standard and a ratio reflecting the efficiency of the source in terms of the standard in producing visual perception can be computed. The standard source is called the candela (a unit of luminous intensity which will be discussed in the succeeding section) and is defined spectrally as the distribution of a blackbody (Section 3.1) at 2042°K (freezing point of platinum).

2.0 CONCEPTS AND UNITS*

flux

Flux is the flow of radiant power and is a directional (vector) quantity.

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*A complete list of units in all possible measurement systems will not be presented. The reader is referred to U.S.A. Standard Nomenclature and Definitions for Illuminating Engineering, RP-16, 16 August 1967, United States of America Standards Institute, for a more complete treatment.

Radiometric Unit - watt:

$\Phi = dQ/dt$*

Luminous (photometric) Unit - lumen**

$\Phi = dQ/dt$. The lumen is tied to the candela for its value. The lumen is the luminous flux emitted into a 1 steradian solid angle. (4π steradian in a sphere) by a point source of one candela.

energy

Radiometric Unit - joule = Q

Luminous Unit - lumen sec = Q (Q_v) = $\int_{0.38}^{0.76} K_\lambda Q_{e\lambda} \, d\lambda$

(See Section A-3.0 for the definition of K_λ.)

intensity

Intensity is flux per unit solid angle from a point source (Figure A-1).

Radiometric unit - watt per steradian:

$I = d\Phi/d\omega$

Luminous unit - candela (or lumen per steradian)

$I = d\Phi/d\omega$. The candela is the standard unit in the photometric system. It is 1/60 of the intensity of one square centimeter of a blackbody at 2042°K.

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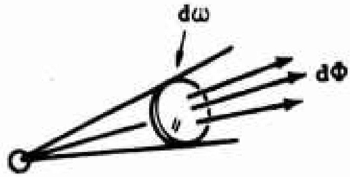
*Symbols for both radiometric and photometric quantities are the same. When a distinction is necessary, a subscript v is used for photometric and a subscript e is used for radiometric. The subscript λ is used when the spectral character of the quantity is important.

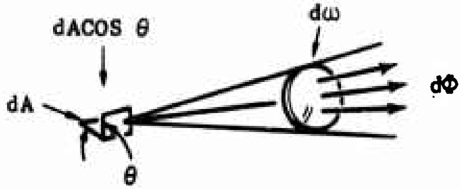
**An additional confusion factor is added by the television industry. It uses a tungsten lamp with a color temperature of 2870°K as a standard radiation source instead of the candela. This source is used to define the 2870 lumen. Because the spectral distribution is different than that of the candela, any sensor calibrations in amps of signal current per lumen will give erroneous results to the system engineer who assumes the spectral distribution of the candela in his radiometric conversion.

INTENSITY



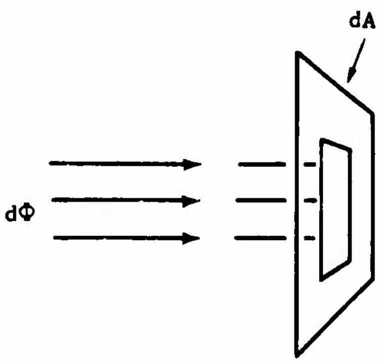
$$I = \frac{d\Phi}{d\omega}$$

LUMINANCE
RADIANCE



$$L = \frac{dI}{dA \cos \theta}$$

ILLUMINANCE
IRRADIANCE



$$E = \frac{d\Phi}{dA}$$

FIGURE A-1. RADIOMETRIC/PHOTOMETRIC DEFINITIONS

radiance/luminance/brightness*

These terms all refer to the intensity of a radiant surface in a given direction per unit projected area of that surface (Figure A-1).

Radiometric unit - radiance:

Watt per steradian per square centimeter:

$L = dI/dA \cos \theta$ where θ is angle of projection to line of sight.

Luminous Unit - luminance or brightness:

Candela per unit area: $L = dI/dA \cos \theta$

In addition to candela per square centimeter, one will commonly encounter in the discipline of displays and imaging systems the luminance units of lamberts and foot lamberts. The lambert, L, is equal to $1/\pi$ candela per square centimeter and the foot lambert, fL, is equal to $1/\pi$ candela per square foot. Luminance conversion factors are tabulated in Table A-1.

*The term brightness or photometric brightness is used interchangeably with the term luminance and when used in this sense has a well defined meaning because it refers only to the physical stimuli reaching the eye (or sensor). Brightness often has an additional meaning in which it refers to the perception of received radiation by the eye. This is a highly variable and subjective process. Care should therefore be taken to clearly distinguish the intended meaning of the term brightness when it is encountered.

TABLE A 1. LUMINANCE (PHOTOMETRIC BRIGHTNESS) CONVERSION FACTORS

1 nit = 1 candela/m^2
1 stilb = 1 candela/cm^2
1 apostilb (international) = 0.1 millilambert = 1 blondel
1 apostilb (German Hefner) = 0.09 millilambert
1 lambert = 1000 millilamberts

Number of → Multiplied by ↘ Equals Number of ↓	Foot-Lambert	Candela/m^2	Milli-Lambert	Candela/^{7} in.^{2}	Candela/ft^2	Stilb
Footlambert	1	0.2919	0.929	452	3.142	2,919
Candela/m^2 (Nit)	3.426	1	3.183	1,550	10.76	10,000
Millilambert	1.076	0.3142	1	487	3.382	3,142
Candela/in.^{3}	0.00221	0.000645	0.00205	1	0.00694	6.45
Candela/ft^2	0.3183	0.0929	0.2957	144	1	929
Stilb	0.00034	0.0001	0.00032	0.155	0.00108	1

emittance/luminous emittance

These terms refer to the radiant (luminous) flux emitted from a surface per unit area of the emitter.

Radiometric unit - emittance:

Watt per square centimeter:

$M = d\Phi/dA$

Luminous Unit - luminous emittance:

Lumen per square foot: $M = d\Phi/dA$

While emittance is the traditional unit for flux emitted from a surface, it is being deemphasized as a term and is being replaced with the term exitance.

irradiance/illuminance (illumination)

These terms refer to the flux density reaching (incident) upon a surface (Figure A-1).

Radiometric unit - irradiance:

Watt per unit area: $E = d\Phi/dA$

Photometric unit - illuminance:

Lumen per unit area: $E = d\Phi/dA$

Illuminance conversion factors are tabulated in Table A2.

TABLE A-2. ILLUMINATION CONVERSION FACTORS

1 lumen = 1/680 lightwatt
1 lumen-hour = 60 lumen-minutes
1 footcandle = 1 lumen/ft^2
1 watt-second = 1 joule = 10^7 ergs
1 phot = 1 lumen/cm^2
1 lux = 1 lumen/m^2

Number of → Multiplied by ↘ / Equals Number of ↓	Footcandles	Lux	Phots	Milliphots
Footcandles	1	0.0929	929	0.929
Lux	10.76	1	10,000	10
Phot	0.00108	0.0001	1	0.001
Milliphot	1.076	0.1	1,000	1

exposure

Exposure is the surface density of energy received. It is also the time integral of irradiance.

Radiometric unit - joule per square centimeter:

Photometric unit - lumen-sec per square centimeter

$$H = \frac{dQ}{dA} = \int E \, dt$$

Exposure is most commonly used with photographic materials.

ratio modifiers of radiant flux

These terms describe on a ratio basis with input (incident) radiation the magnitude of a change from the incident radiation for the processes of radiant absorbtion, radiant reflection, and radiant transmission. The terms are the same in both the radiometric and photometric systems except that the adjective luminous may proceed the photometric version. The ratios are dimensionless.

Absorbtance $\alpha = \frac{\Phi \text{ absorbed}}{\Phi \text{ incident}}$

Reflectance $\rho = \frac{\Phi \text{ reflected}}{\Phi \text{ incident}}$

Transmittance $\tau = \frac{\Phi \text{ transmitted}}{\Phi \text{ incident}}$

3.0 RADIOMETRIC/PHOTOMETRIC CONVERSION

Any radiation invisible to the human eye (as defined by the photopic eye sensitivity curve) has no photometric value. Any radiation that causes visual sensation can be converted to photometric units from radiant units using the candela and as a standard and the photopic eye sensitivity curve. The peak value of visual sensation to radiant flux occurs at 0.555 μm and at that point 1 watt is equal to 680 lumens. For any other wavelength of monochromatic visible light the conversion from watts to lumens is the product of the maximum sensitivity and the normalized photopic eye sensitivity, V_λ. [(680 lumens/watt)(V_λ) = conversion value at λ.] The ratio of photopic flux to radiant flux is called the luminous efficacy (luminosity factor); its symbol is K and its units are lumens per watt:

$$K_\lambda = \frac{\Phi_{v\lambda}}{\Phi_{e\lambda}} = \frac{\text{spectral luminous flux, lumens}}{\text{spectral radiant flux, watts}}$$

The maximum value of K_λ is K_{max} = 680 lumens/watt at 0.555 μm. K can also be evaluated for a spectrum as well as monochromatic radiation, then then

$$K = K_{max} \frac{\int_0^\infty V_\lambda \Phi_{e\lambda} d\lambda}{\int_0^\infty \Phi_{e\lambda} d\lambda}$$

where $\Phi_{e\lambda}$ is spectral radiant flux. It takes only a slight modification of this equation to give the relationship for total luminous flux as a function of spectral radiant flux

$$\Phi_v = K_{max} \int_0^\infty V_\lambda \Phi_{e\lambda} d\lambda$$

The luminous efficiency of one wavelength of visible radiation in producing visual sensation is measured as a ratio of the efficacy of that wavelength against the maximum efficacy. The symbol for efficiency is V and $V_\lambda = K_\lambda / K_{max}$. The term relative luminosity is synonymous for luminous efficiency.

APPENDIX B

GLOSSARY AND TEXT REFERENCE

absorbtance: see Appendix A

afocal: an optical system with no finite conjugates (i.e., both the object and the image are at infinity as in the case of a simple telescope).

air glow: (Section 4.3) radiation issuing from the upper atmosphere as a result of photochemical reactions in the upper atmosphere.

air mass: (Section 4.3) a measure of atmospheric path length. One air mass is the path length associated with a radiant path along the zenith. Any depression from that angle introduces addition path length in air masses.

alias: (Section 4.7) a spurious signal introduced into the video signal, or at the display, by using inadequate sampling rates in terms of the amount of information to be sampled.

angular subtent: size of a sensing element expressed as an angle in terms of the focal length of the system and proportionality constants.

aperture correction: (Section 4.7) electronic processing of the video signal in order to compensate or correct frequency response deficiencies in the scanning aperture.

aperture response: synonym for system MTF.

aspect ratio: ratio of horizontal to vertical dimension of the undistorted displayed image.

bandwidth: (Section 4.7) size of the electronic channel in terms of the amount of cyclical information it can transmit per unit time.

bias current (voltage): that current passed through a radiation detector so that a conductivity change in the detector resulting from radiation incident on the detector can be detected as a current or voltage change.

blackbody: (Section 3.1) ideal thermal radiator

bloom, flare, halo: (Section 4.5) image defects characterized by image spreading and masking of adjacent information as a result of exceeding the intrascene dynamic range of the sensor.

brightness: see Appendix A.

brightness distortion: (gamma distortion) nonlinear reproduction of scene brightness and contrast values.

cold stop: a shield used in FLIR front ends to prevent thermal radiation from extraneous sources from reaching the scanning detectors.

collimator (collimation): an optical instrument or system which provides an image at infinity. They are used in the laboratory to simulate distant targets. They are used in displays (Section 4.2) to allow the observer to focus simultaneously on the display and on the distant scene.

color temperature: the temperature at which a blackbody must be operated to give a color (chromaticity) matching that of the source in question.

conjugates: any pair of interchangeable image and object points of an optical system.

contrast: (Section 3.2) any of the various definitions expressing the relative radiances (brightnesses) between any two portions of the viewed scene.

contrast enhancement: any technique to improve contrast in the viewed scenes. It may take the form of aperture correction (edge sharpening) or gated illumination.

CRT: cathode ray tube used in imaging systems as a display.

convolve (convolution): the dictionary definition is "to roll together." The output signal from a linear system is the convolution of the system impulse response (point or line spread functions for imaging systems) with the input signal function. To convolve two functions, the functions are aligned on the same axis. One function is then slid past the other. The convolution is the plot of the common area between the two functions versus the position of the sliding function. (See any standard text on Fourier integrals or transforms.)

critical fusion frequency: the lowest repetition rate at which the fluctuation of a pulsating light source cannot be seen.

D* (detectivity): figure of merit for detector performance that is inversely proportional to the noise characteristics of the detector and proportional square root of the detector area.

dark current: an electrical current which flows in detectors and TV camera tubes even when no optical flux is falling on the detector. It can be a significant source of shot noise, and in some TV camera tubes it can limit dynamic range at higher temperatures.

dc restoration: adding to the video signal or providing to the video signal a reference signal to restore to the video signal the lower frequency components of the imaged scene.

direct view device: an image intensifier or image converter viewed directly by the human eye, usually by means of an eyepiece.

display:	(Section 4.2) any device or mechanism which converts the video signal to radiant images for viewing by the observer.
DMF (demand modulation function):	(Section 4.1) the contrast threshold requirement for the observer as a function of spatial frequency considered in the context of the environment of the observer.
duty cycle:	an expression for relative amount of time that a device or system is in an active mode.
dwell time (FLIR):	that period of time in which the scanned detector will take to traverse a distance equal to its active dimension in the scan direction. It is related to frame rate and interlace factors.
dynamic range:	the range of radiant values that can be reproduced by a device or system without loss of information due to saturation. The dynamic range may apply to different parts of the same scene (intrascene dynamic range) or it may apply from frame to frame (interscene dynamic range).
dynodes:	an electrode in a photomultiplier imaging tube which provides electron gain.
efficacy (luminous):	see Appendix A.
efficiency (luminous):	see Appendix A.
emissivity:	(Section 3.1) a ratio indicating the closeness to which a graybody approaches the ideal blackbody at the same temperature.
emittance:	see Appendix A.
energy (radiant):	see Appendix A.
entrance, exit pupil:	image of the aperture stop as viewed from object space (entrance pupil) and image space (exit pupil) (reference Fundamentals of Optics, Jenkins and White).
equivalent signal bandwidth (spatial):	the integral over all spatial frequencies of the square of the modulation transfer function.

eye relief: distance from an eye piece where the eye is placed for optimum viewing.

exitance: see Appendix A.

exposure: see Appendix A.

f/ (f number or relative aperture): (Section 4.4) ratio of the effective focal length of an optical system to its useable or clear aperture diameter.

faceplate: that part of a TV pickup tube which interfaces with the radiant image formed the system optics. The face plate may be of special design to compensate for some field curvature of the optics. Also the viewed surface of a display tube.

fiber optics: an assemblage of small "light pipes" wherein optical radiation is relay d from one point to another by the physical properties of fiber optics. In use with imaging systems the arrangement of the fibers in a bundle is carefully controlled and the fiber optic bundle is used to relay radiant images.

field: one of the two or more equal parts into which a frame is divided in interlaced scanning.

field of view: (Section 4.4) the angular measure of the displayed scene. Instantaneous field of view is the angular subtense of a detector element in a FLIR set.

flat field: the result one hopes to approach with a rastered image wherein the raster is not visible and hence the image is "flat."

flicker: (Section 4.7) display variation in radiant intensity caused by discrete nature of framing. The frame rate is picked to be sufficiently high to minimize flicker distraction and irritation. (See critical fusion frequency.)

flux: See Appendix A.

<u>focal length</u>:	(Section 4.4) that property of lenses and curved mirrors which determines where and what size the image of an object will be formed.
<u>frame</u>:	the total area, occupied by the image, which is scanned.
<u>frame rate</u>:	(Section 4.7) the reciprocal of the time in seconds between the appearance of successively new images. Note, in order to preserve electrical bandwidth while maintaining sufficiently high flicker rate the frame may consist of multiple fields through use of interlace.
<u>gain</u>:	amplification of the video signal. Gain controls are often miscalled contrast controls.
<u>gamma</u>:	slope of the input irradiance versus transducer output curve, on log-log scales.
<u>gate (gating)</u>:	a system is said to be gated when it is receptive to incoming signals (i.e., turned on) for a specific period of time. In imaging systems image intensifiers are often gated by application and removal of high voltage to the intensifier stage such that only radiant information from a certain range will be accepted.
<u>gray shades</u>:	a measure of the dynamic range of a display or system using a target with a set of stepped contrast levels. The most common target uses a logarithmic step of $\sqrt{2}$ between brightness levels.
<u>graybody</u>:	(Section 3.1) a thermal radiator whose constant spectral emissivity is less than unity.
<u>illumination</u>:	see Appendix A.
<u>impulse response</u>: (spatially)	the system or component response to a geometrical point or line source of radiation.
<u>infrared</u>:	that spectrum of optical radiation with wavelengths longer than the spectrum of visible radiation.

inherent, apparent contrast: (Section 3.2) refers to the contrast at zero atmospheric path length and then to the contrast as it appears after modification by the atmosphere.

integration time: (Sections 4.1, 4.5) the time a sensor, either the eye or electro-optical device, uses to collect photons to form an image.

intensity: see Appendix A.

interlace scanning: a scanning process in which the scan lines are spaced an integral number of scan lines apart and in which adjacent lines are scanned in successive fields. The interlace is usually 2:1 in television systems but may be more for FLIR systems.

IR: contraction for infrared.

irradiance: see Appendix A.

Kell factor: in television the ratio of effective vertical resolution to the number of active scan lines. It is approximately 0.7.

kinescope: a type of display utilizing a CRT.

lag: (Section 4.5) in TV pickup tubes, the after image resulting from incomplete discharge of the electron image by the scanning electron beam.

liminal contrast: contrast threshold for human perception of the contrast difference.

line spread function: (Section 3.3) the distribution of radiation in the image of a line. It is analogous to the impulse response of an electrical network. It is the inverse Fourier Transform of the Optical Transfer Function.

luminance: see Appendix A.

microphonism: generation of circuit noise by vibration of the component or system.

minimum resolvable temperature difference (MRT) resolvable temperature difference (RT): the former term is the lowest effective blackbody target to background temperature difference for "The Standard Periodic MRT Test Pattern" at which the pattern is resolvable by an observer. Unlimited viewing time is allowed. The system is operated in a noise-limited but linear mode and MRT is determined as a function of the fundamental frequency of the test pattern.

the latter term refers to any similar measurement where the exact requirements for the MRT measurement are not met as would be the case if a different target was used or if the system is operated in a nonnoise limited mode.

modulation threshold function: the required modulation amplitude of a sine wave pattern as a function of spatial frequency for perception by the human eye. Under some circumstances it can be considered the demand modulation function.

MTF (modulation transfer functions): (Section 3.3) the modulus of the OTF normalized to a maximum value of one. (The normalized amplitude response to spatial sine waves as a function of spatial frequency.)

NETD (noise equivalent temperature difference): (FLIR) the effective blackbody target to background temperature differences in a low frequency standard test pattern which produces a peak-to-peak signal to rms noise ratio of one at the output of an external standard electronic filter. The concept can be extended to non-standard test patterns and filters.

noise figure: (Section 3.4) a circuit figure of merit usually applied to low level preamplifiers. It is a measure of the noise added by the amplifier to the noise at the input. It is defined as the ratio of the S/N power ratio at the output of the circuit divided by the S/N power ratio at the input.

noise: (Section 3.4) spurious or unwanted disturbances that tend to mask the desirable signal.

objective: optical element located closest to the object which forms a real image of that object.

OTF (optical transfer function): (Section 3.3) is a measure of the spatial frequency response of a system or component. It is the Fourier transform of the system line spread function. The OTF is complex, having a phase as well as an amplitude term. The absolute value of the OTF is the MTF.

overscan: the practice of scanning the electron beam in TV pickup tubes or CRT's beyond the active area of the component.

path luminance: (radiance) (Sections 3.2, 4.3) light in the optical field of view of a system that does not originate from the imaged target area.

photocathode: (Section 4.5) the active part of a TV pickup tube in which radiation is converted to electron flow.

photoconductive: a physical phenomena which produces useful electrical signal as a result of incident radiation upon a detector or photocathode of a pickup tube. In photoconduction photons free electrons in a semiconductor device. The free electrons then are responsible for a change in the conductivity.

photoemission: a physical phenomenon which produces free electrons which may be collected by an accelerating electrode to produce an electron gain which ultimately results in a substantial signal current. In photoemission the incident photon, provided it has sufficient quantum energy, will knock free an electron from the photoemissive surface of a pickup tube.

photon: a quantum or particle of light, having energy inversely proportional to wavelength.

pickup tube: (Section 4.5) (signal generating image tube) radiation transducer for converting radiant images to TV signals. It has a photocathode and a scanning electron beam which generates a modulated electrical signal.

point spread function: the distribution of radiation in the image of an object point.

PTF (phase transfer function): (Section 3.3) the argument of the OTF. It is the phase change at each spatial frequency due to a component or a system.

quanta, quantum: (Section 3.1) packets of radiant energy as described by the particulate model for light.

quantum efficiency: a measure of the efficiency that a photosensitive surface has in converting quanta to free electrons. It is a spectral quantity and is a ratio of electrons to quanta.

radiance: see Appendix A.

raster: the predetermined pattern of scanning lines used to cover the optical field of view.

ray: a geometric concept of light motion in which light is thought to travel in a straight line.

ray tracing: a geometrical method of evaluating optical system performance by tracing the path of several rays through the system and evaluating the resultant image.

reflectance: see Appendix A.

relative aperture: same as f/number. This ratio is a measure of the light gathering ability of an optical system and is often called the "speed" of the system. This same parameter is often measured as a function of the half angle defined by the aperture and focal length in which case it is called the numerical aperture.

relay lens: an auxiliary lens used to relay optical images through an optical system. Their usual function is to prevent the ray bundle containing the optical information from becoming unmanageably large.

resolution: (Section 3.3) a measure of the ability of an imaging system to distinguish close objects. Its use is being replaced by MTF techniques.

resolution limit: (Section 3.3) historically the resolution limit was determined from bar charts with the measure of resolution being the smallest

resolution limit: (continued)	resolvable bar target. In the context of imaging systems it is the point at which the threshold requirements of the eye are identical to the available modulation. This is the point at which the DMF intersects the MTF function of the system.
scattering:	the redirection of light from its incident direction by randomly located scattering centers in the transmitting medium.
scintillation:	the variation in target intensity and/or angular position due to inhomogenities in the optical path. Synonyms are shimmering, twinkling and boil.
scotoscope:	a night vision device.
sensitivity:	(Appendix A, Section 4.5) the measure of a TV pickup tube's conversion of radiant power to electrical signals. The units are amps/watt and the quantity may be expressed spectrally.
sky ground ratio:	(Section 4.3) for the case of downward looking optical path, it is the ratio of the luminance of the horizon sky in specific direction (defined by the geometry of the observer and the sun) to the zero range luminance of the ground. (Reference: Duntley JOSA V:38 Number 2, February 1948.)
signal-to-noise ratio:	(Section 3.4) ratio of the desirable signal to unwanted masking signals. There are several methods of expressing the ratio so it is important to be aware of the particular method or system used.
signal transfer function:	(Section 4.5) the photopic luminance output of the system as a function of the input target-to-background temperature difference in a standard test target for given gain, brightness and other applicable control settings.
SNR_D:	(Section 4.1) display visual signal-to-noise ratio.

spatial frequency: (Section 3.3) relates to the concept that object shapes can be described by Fourier methods similar to those used in describing electrical pulse shapes and that all objects can be described in terms of superposition of sine waves of intensity distribution of varying period expressed in appropriate units.

spatial invariance: (stationarity) independence of the impulse response or the line spread function on the source position within the object plane.

spectral: (Section 3.1) adjective relating to wavelength dependent properties.

specular reflection: reflection from a mirror-like surface.

speed: that quality of a lens or mirror system that determines the rate that photons enter an area of the image. Speed is often loosely interchanged with f/number but is technically proportional to the inverse square of the f/number.

spurious resolution: (Section 3.3) a reversal of the position of white and black from object to image at particular spatial frequencies due to the phase shift of the OTF at those frequencies.

stops: (Section 4.4) an aperture introduced into the imaging optics in order to limit the amount of light entering the system or to limit the field of view of the system. The former stop is called an aperture stop and the latter is called a field stop.

stop (f/stop): most optical systems and lenses with a variable aperture stop (diagram) indicate the f/(and hence the relative image plane irradiance) by a standard series of marked f/ positions called f/stops. Each stop is a factor of $\sqrt{2}$ from the other stops in the series. The change in irradiance between stops is then a factor of 2 as irradiance varies as the square of the f/. The common f/stop positions are f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16 and f/22.

sweep efficiency: (scanning efficiency) a measure of the proportion of the frame time actually used in scanning the imaged scene.

tonal transfer: the transfer of brightness values through the system.

T-number: (Section 4.4) the f/number corrected for transmission losses in the optics and is equal to f/number divided by the square root of the transmission.

transmittance: see Appendix A.

underscan: (Section 4.5) the practice of scanning less than the available sensitive area of a TV pickup tube or a display.

vignetting: loss of image radiance due to obscuration of some part of the optical path inside the optical system. In addition to vignetting losses, usually due to a stop, the image radiance falls as $\cos^4$ function of the half angle of the field of view.

zoom: (Section 4.4) refers to the ability to change the field of view of an optical system and to "zoom in" or magnify an area of particular interest.

APPENDIX C

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